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ADMINISTRATIVE INFORMATION

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NOVEL CERAMIC MATRIX COMPOSITES FOR DEEP SUBMERGENCE PRESSURE VESSEL APPLICATIONS

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ABSTRACT

Novel ceramic matrix composite tubes for deep submergence pressure vessel applications have been fabricated by the DIMOX™ directed metal oxidation process. These SiC/Al_2O_3 composite tubes have an eight percent lower weight-to-displacement ratio, approximately five times greater thermal conductivity, and more than 50% higher fracture toughness than a tube fabricated from alumina ceramics. Additionally, the SiC/Al_2O_3 composite tubes have a sixty percent lower weight-to-displacement ratio and a 12 times greater thermal conductivity than Ti-6Al-4V alloy tubes. Processing information, hydrostatic implosion test results, and mechanical test data will be discussed.

INTRODUCTION

Deep submergence systems require pressure resistant capsules with low weight-to-displacement ratios (≤ 0.5) for the successful, efficient performance of their missions[1,2]. A large positive buoyancy can greatly enhance vehicle payload, operational range, and speed, whereas poor hull design, construction from heavy materials, or the use of external buoyancy materials (such as syntactic foam) can have deleterious effects on systems cost and operation. There is some movement away from accepted construction materials, like Ti-6Al-4V alloy, toward materials with lower weight-to-displacement ratios, such as ceramics and ceramic matrix composites.

To arrive at an operationally usable external pressure housing of ceramic material, several fabrication and design problems need to be solved that have, in the past, worked against the acceptance of such housings by the ocean engineering community. Not the least among these problems is the economical fabrication of large ceramic cylinders. Alumina ceramics have met with some limited success, but it is clear that new technologies are needed to produce large scale net, or near-net shape ceramic cylinders. To this end, the Naval Ocean Systems Center in San Diego, CA, and Lanxide Corporation, Newark, DE, set out to demonstrate the viability of fabricating ceramic composite submersible cylinders by the DIMOX™ directed metal oxidation process, a unique process patented by Lanxide Corporation. The initial goal is to fabricate and test 15, 30 and 51 cm (6, 12, and 20 inch) diameter tubes (L/D = 1.5) using this process.

BACKGROUND

Ceramics, by their nature, are inherently brittle materials. Although very strong and hard, their resistance to crack propagation is low, often leading to catastrophic failure of the part. The strength of ceramics is greatly affected by their microstructural uniformity and homogeneity. Flaws such as voids, pores, impurities, cracks, and microcracks can strongly influence mechanical properties. Unfortunately, these are common defects associated with standard forming and densification methods used in the ceramics industry, and cannot be easily avoided. Due to these factors, ceramics exhibit a sensitivity to point contact loading, which might occur during handling, maintenance, and routine operation of the submersible. Since such occurrences are inevitable, steps must be taken either to protect the vehicle to improve its survivability, or else select a construction material possessing properties better suited for this type of application. Whatever the material, these applications require that pressure vessels be available in a broad range of sizes. The overall viability of ceramics as a material for pressure vessels will depend not only on performance but also on the technical and economic feasibility of the manufacture of relatively large shapes.

Aluminum oxide is one ceramic material that has received a considerable amount of attention as a candidate for this application[1-5]. Its favorable mechanical properties include high compressive and flexural strengths, high elastic modulus, resistance to corrosion, and relatively low cost. However, fabrication issues, particularly for large scale applications, are of considerable concern. Forming and handling of the green ceramic body, densification, and machining of the fired part can be difficult and labor intensive and present challenging technical issues that must be surmounted. Green body forming by isostatic pressing is a well established technique in which a desired shape is produced by compacting a prepared powder and binder mixture in preshaped tooling using hydrostatic pressure. This is an effective means of producing even relatively large parts but requires proper powder preparation, tooling investments, and, for big parts, the use of scarce large pressure chambers. Parts produced by this and other traditional ceramic fabrication processes must then be densified by sintering, resulting in up to 30 volume percent shrinkage of the component. This, along with warping, slumping, and cracking often associated with the sintering of large ceramic bodies, makes net shape forming difficult if not impossible to achieve. Thus, extensive costly machining of the very hard ceramic body is required to achieve high tolerances.

TECHNOLOGY OVERVIEW

Lanxide Corporation has demonstrated a unique and highly versatile process for the fabrication of fully dense ceramic matrix composites. Specifically, the DIMOX™ directed metal oxidation process is the generation of composite matrices formed by literally "growing" them from commodity metals via a novel oxidation process which bonds filler media into cohesive, high performance composites (Figure 1). Such filler media may include ceramic reinforcing particles, fibers, or whiskers. In the case of particles, the filler material can be shaped into a preform by any "classic" ceramic shape forming technique, such as slip casting, injection molding, or pressing. A barrier material is applied to the surface of the preform to confine the matrix growth to the preform, thus defining the shape. A key feature of the process is that the filler materials are not displaced or disturbed during the matrix formation, enabling net or near net shape fabrication of complex geometries.

These LANXIDE™ ceramic matrix composite matrices are a three dimensionally interconnected ceramic structure, containing one or more metallic phases that may or may not be three dimensionally interconnected, depending upon processing conditions. The ceramic matrix composites behave mechanically as tough, strong ceramics, in some cases having three to four times the fracture toughness of ceramics produced by conventional processes. Further information about the processing and general characteristics of these composites is available in the literature.[6]

DESIGN DEFINITION

The design selected for the NOSC ceramic housing utilizes monocoque cylinders with a length/diameter ratio of 1.5 and a wall thickness/diameter ratio of 0.034. The ends of the cylinders are capped by metallic joint rings securely bonded to the ceramic with epoxy adhesive. These rings mate either with removable metallic stiffeners or similar rings bonded to ceramic hemispherical bulkheads. The removable ring stiffeners align the ends of the cylinders during assembly, contain the O-ring seals, and serve as components of mechanical joints for fastening together individual cylinders and hemispheres into a single housing assembly. The advantages of monocoque cylinders (supported radially at the ends by removable metallic stiffeners) over cylinders with integral ceramic ring stiffeners are reduced fabrication costs (resulting from the simplicity of the geometry) and an increase in the diameter and volume of internal payload envelope.

MATERIALS

The versatility of the DIMOX™ directed metal oxidation process allows for the incorporation of a wide range of filler particle chemistries, morphologies, and size distributions as preform materials. This unique ability permits individual material systems and their properties to be tailored to the specific requirements of a given application. Preliminary studies with a variety of filler sizes showed that a 500 grit silicon carbide composite with a grown aluminum oxide matrix (termed LANXIDE™ 90-X-089 SiC reinforced Al_2O_3 ceramic matrix composite and referred to hereafter as "90-X-089 CMC") demonstrated acceptable or better mechanical properties than those required for this application.

Table 1 shows a comparison of mechanical properties for 90-X-089 CMC and 94 percent alumina ceramic. The 90-X-089 CMC meets or exceeds the specified mechanical properties for this application and has distinct advantages over alumina in several areas. The lower density, 3400 kg/m^3 (versus 3620 kg/m^3 for 94 percent aluminum oxide ceramic and 4430 kg/m^3 for Ti-6Al-4V) provides for increased buoyancy and therefore increased vehicle payload capacity. The higher fracture toughness is especially important in inhibiting initiation and propagation of cracks on the ceramic bearing surfaces bonded to metallic joint rings during the repeated pressurizing and depressurizing of the pressure housing while in operation, reducing the risk of catastrophic failure. The large advantage in thermal conductivity is especially important for conduction of heat produced by functioning equipment inside the pressure housing to the outside environment. The 90-X-089 CMC also possesses a higher elastic modulus, compressive strength, and thermal conductivity than Ti-6Al-4V alloy commonly used for construction of pressure resistant housings on deep submergence vehicles.

CYLINDER FABRICATION

The fabrication of 15 cm (6 in.) diameter model scale cylindrical test specimens served to demonstrate the applicability of the DIMOX™ directed metal oxidation process to the production of cylindrical monocoque pressure housings for 62 MPa (9,000 psi) service (Figure 2). Silicon carbide powder was consolidated into cylindrical preform shapes by a simple technique providing less than 1% dimensional changes during processing; hence, little or no green machining of the preform is required. Appropriate surfaces of the preform are then coated with a barrier material to confine the "growth" of the matrix to the boundaries of the preform, after which it is placed in a refractory boat in contact with aluminum alloy. The boat is put into a furnace and heated to a temperature of about 1000°C. When growth is completed, the composite is furnace cooled. Some grit blasting may by required to remove residual alloy from the surface of the composite. Light machining or touch up grinding may be necessary depending on tolerance and/or surface finish requirements, but only a small fraction of the total volume of the composite cylinder is removed. Further machining of the cylinder ends may be required for proper fit of joint rings. The cylinders are inspected visually and ultrasonically for defects before pressure testing.

TEST PROCEDURES AND RESULTS

Five model scale 15 cm (6 in.) diameter cylinders (Figure 2) were subjected to external pressure testing. Prior to the tests, all but the first cylinder were instrumented with electric resistance strain gauges and an acoustic emission transducer using procedures previously described[1-4]. The ends of the cylinders were enclosed with titanium joint rings bonded to the ceramic matrix composite (CMC) with epoxy resin (Figure 3). Prior to performance of proof tests to 69 MPa (10,000 psi) the cylinders were closed off with hemispherical titanium bulkheads providing radial support to the ends of the cylinder, and sealed by wrapping the exterior of the joint with vinyl electrical insulation tape (Figures 4 & 5). For implosion testing the hemispherical bulkheads were replaced with plane aluminum bulkheads designed to provide radial support to the ends of the cylinder (Figures 6 & 7) at pressures in excess of 69 MPa (10,000 psi). Testing was performed in a pressure vessel having electrical feed-throughs which allowed the strain and acoustic emission signals to be externally monitored. Pressures were increased in ~7 MPa (1,000 psi) increments until the maximum desired pressure was achieved. The strains were recorded at each pressure increment, while the acoustic emissions were recorded continuously.

The test parameters and results are presented in Table 2. The first test performed on cylinder A (SN01) was a preliminary one to bracket the performance of the new material, and thus was not instrumented. In the next three test series utilizing cylinders B (SN02), C (SN03) and D (SN04), the cylinders were subjected to various numbers of proof tests (from zero to four) prior to determining the critical pressure for implosion. The E (SN05) cylinder was subjected to four proof tests to a maximum pressure of 69 MPa (10,000 psi) and then pressure cycled one hundred times to a design pressure of 62 MPa (9,000 psi). This is the equivalent of repeatedly submerging the cylinder to an initial depth of ~6,770 m (~22,000 ft.) for the first four dives, and then to ~6,100 m (~20,000 ft.) for the next 100 dives. While being pressure cycled, the cylinder was subjected to the design pressure of 62 MPa (9,000 ksi) for a total of 170 hours. Examination of the component at the end of this sequence showed no damage. The E (SN05) cylinder was subsequently pressure cycled to 93 MPa (13,500 psi) to establish its tolerance to infrequent overpressurizations encountered during excursions of the autonomous underwater vehicle, AUV, beyond the 6,100 meter design depth. The cylinder successfully withstood 100 cycles to simulated 9,150 m depth without failure. The cumulative duration of sustained loadings was 196 hours.

Examination of the fragments from imploded composite cylinders indicated that the failure mechanism was elastic buckling. In comparison to previously tested 94 percent alumina cylinders the fragments were rather large. In the first test, A (SN01), a subsized aluminum tube coated on its exterior with a rubber layer was inserted inside the composite tube prior to attaching the end caps. The function of this insert was to mitigate the shock waves generated by implosion so that larger fragments would remain after implosion facilitating inspection of fracture surfaces. At ambient pressures, an annular clearance of several millimeters existed between the outside diameter of the rubber and the inside diameter of the composite. Examination of the post-test composite fragments showed that during testing the rubber had extruded into the cracks which ultimately became the fragment edges. This can be interpreted to mean that the cylinder had buckled prior to catastrophic failure and subsequently collapsed onto the rubber lined aluminum tube. Additional evidence for buckling is that the mean nominal compressive hoop stress at implosion, 172.5 MPa (250,000 psi), is lower than the material's uniaxial compressive strength of 195.0 MPa (283,000 psi) and that the critical pressure is close to the value calculated for buckling of a cylinder using the von Mises equations for prediction of elastic instability[5].

The recorded compressive strains on the cylinders were linear to the moment of implosion. During repeated pressurizations, a 0.02 percent set was observed after the first pressurization to 62 MPa (9,000 psi); the material behaved in a perfectly elastic ma er during subsequent pressurizations to ign pressure. Fewer acoustic emissions were recorded on the CMC cylinders than on identical alumina ceramic cylinder during the first pressurization. During subsequent pressurizations to 62 MPa (9,000 psi) the acoustic emissions ceased, indicating total absence of any crack growth, or relative displacement between crystals in the body of the material.

DISCUSSION

There are obvious structural advantages in using monolithic ceramics and ceramic matrix composites in submersible vehicle applications. These materials have superior specific elastic moduli and specific compressive strengths when compared to metals. The critical hydrostatic pressures for failures of long cylinders of several candidate materials are compared in Figure 8. Two types of failure mechanisms for cylinders are shown on the plot: the linear relationships represent yield or ultimate strength failures and the curved relationships represent elastic buckling of infinitely long monocoque cylinders without stiffeners. At a given weight to displacement ratio, the cylinder will fail by the mechanism requiring the least magnitude of pressure. The plot shows that long cylinders of the three materials will fail by buckling. The ceramic and the composite will out perform the titanium alloy over the total range of weight/displacement and pressure.

In the tests performed in the present program, the 90-X-089 CMC failed at critical pressures similar to the identically sized 94 percent Al_2O_3 previously tested[1]. In agreement with the calculations, the CMC cylinders had an 8% buoyancy advantage over 94 percent alumina ceramic cylinders supported radially at the ends with identical titanium hemispheres.

The 90-X-089 CMC has also demonstrated superior cyclic fatigue properties than the 94 percent alumina. Test data from previous NOSC test programs has shown that alumina tends to spall on the plane bearing surfaces of the cylinder ends during cyclic pressurizations. These spalls increased in size with each pressure cycle until the ceramic cylinder imploded catastrophically[1]. The number of load cycles required for crack initiation varied with the type of gaskets and bearing stress.

The superior resistance of CMC to crack initiation and propagation was demonstrated by subjecting material test specimens to repeated uniaxial compression loading on specimens measuring 9.5 mm diameter by 19 mm long until failure occurred due to progressive spalling that initiated on the plane bearing surfaces. Two types of tests were run. In the first test a specimen of each type (96% alumina and SiC/Al_2O_3 composite) was subjected to ~10,000 cycles between 0 and -1.0 GPa and then examined. As shown in Table 3, a 7 mm long crack had propagated parallel to the stress axis in the 96% alumina sample but none had propagated in the SiC/Al_2O_3 composite. The alumina sample was subjected to an additional 2,000 cycles and on reexamination, the original crack had extended another 1.5 mm and a new crack initiated. The composite sample was subjected to an additional 26,680 cycles at a higher stress (1.5 GPa) prior to failing. In the second test in Table 3, a small crack was put into the ends of each of the specimens with a microhardness indentor. The 96% Al_2O_3 specimen was subject to 10 cycles between 0 and 1 GPa and examined. A 2.3 mm crack had initiated from the end, but it was not associated with the indentation crack. After another 90 cycles, this crack had extended to 6.6 mm. The SiC/Al_2O_3 composite showed no crack initiation after 20,000 cycles to -1 GPa (145,000 psi). Therefore the number of cycles to appearance of spalling and subsequent failure was significantly larger for the CMC than for the 94 percent alumina ceramic for the same magnitude of bearing stresses. This improvement in fatigue life is probably attributable to the higher fracture toughness of the CMC, and its better resistance to subcritical crack growth.

Another important advantage of the composites with respect to Ti alloys or monolithic aluminas is their thermal conductivity. As shown in Table 1, the 90-X-089 CMC is ~12 times better than Ti-6Al-4V and ~6 times better than 94 percent Al_2O_3. Thus, submersibles made with the 90-X-089 CMC can maintain lower internal temperatures, which is an important consideration for electronic components, when packed to capacity with heat generating equipment.

Although higher purity aluminas have better specific properties than 94 percent alumina, they are much more difficult to fabricate in the large sizes required for most deep submergence vehicles. This should not be a limitation for composite cylinders and hemispheres fabricated from the 90-X-089 CMC by the DIMOX™ directed metal oxidation process. Further, as the technology matures, optimized versions of the 90-X-089 CMC can be expected to yield improved properties. Lanxide is currently in the process of fabricating a 31 cm (12 in.) diameter by 46 cm (18 in.) long cylinder. The pressure housing development program also calls for the fabrication of a several 51 cm (20 in.) diameter by 76 cm (30 in.) long cylinders and similarly sized hemispheres.

SUMMARY

Model scale 15 cm (6 in.) diameter ceramic matrix composite cylinders consisting of an alumina/aluminum composite matrix filled with silicon carbide particles have been fabricated at Lanxide Corporation by the DIMOX™ directed metal oxidation process and pressure tested to destruction at the Naval Ocean Systems Center. While the critical pressures for failure are similar to that of similarly sized 94 percent alumina cylinders, the composite material has a lower density and thus a buoyancy advantage over the monolithic ceramic material. In cyclic compression tests to stress levels encountered in cylinders at design depths, the composite's fatigue life has proven to be superior to alumina. Due to near-net shape fabrication methods, it is projected that the composite will also have a cost advantage over alumina, as well as over titanium alloys for large pressure housings. This is particularly true for irregular housing shapes, like cylinders with ring stiffeners, hemispheres with bosses around penetrations, shells with irregular radii, etc. Finally, the superior thermal conductivity of the composite will allow greater dissipation of heat from electronic components contained by the

pressure housings without the use of heat exchanger coils.

The tests performed on the five ceramic metal composite model scale monocoque cylinders with T/D_0 = 0.034 and L/D=1.5 have demonstrated that this monocoque cylinder configuration supported radially at its ends by bulkheads not only provides a 0.47 weight/displacement ratio, but is also well suited for service depths of 6,100 meters (with a safety factor of 1.85) and intermittent excursions to 9,150 meters depth (with a safety factor of 1.23). This performance can be duplicated by titanium cylinders with identical safety factors only by incurring a 100 percent decrease in buoyancy that must be compensated for by the addition of syntactic foam. The added weight of the titanium cylinders and of the syntactic foam would increase the weight of the housing assembly in air by 200 percent.

REFERENCES

1. J. D. Stachiw and J. L. Held "Exploratory Evaluation of Alumina Ceramic Cylindrical Housings for Deep Submergence Service: The Second Generation NOSC Ceramic Housings" NOSC TR 1176, 1987, Naval Ocean Systems Center, San Diego, CA.

2. J. D. Stachiw, "Pressure Resistant Ceramic Housings for Deep Submergence Systems," NOSC TR 1294, 1983, Naval Ocean Systems Center, San Diego, CA.

3. J. D. Stachiw, "Exploratory Evaluation of Alumina Ceramic Cylindrical Housings for Deep Submergence Service: The Third Generation NOSC Ceramic Housings, NOSC TR 1314, Naval Ocean Systems Center, San Diego, CA.

4. J. D. Stachiw, "Exploratory Evaluation of Alumina Ceramic Housings for Deep Submergence Service: The Fourth Generation Housings," NOSC TR 1355, 1990, Naval Ocean Systems Center, San Diego, CA

5. J. D. Stachiw, "Design Parameters for Glass and Ceramic Underwater Structures", *Ceramic Age*, pp. 51-6, June, 1965.

6. M. S. Newkirk, et al., "Preparation of Lanxide™ Ceramic Matrix Composites: Matrix Formation by the Directed Oxidation of Molten Metals," *Ceram. Eng. Sci. Proc.*, 8 [7-8], pp. 879-885, 1987.

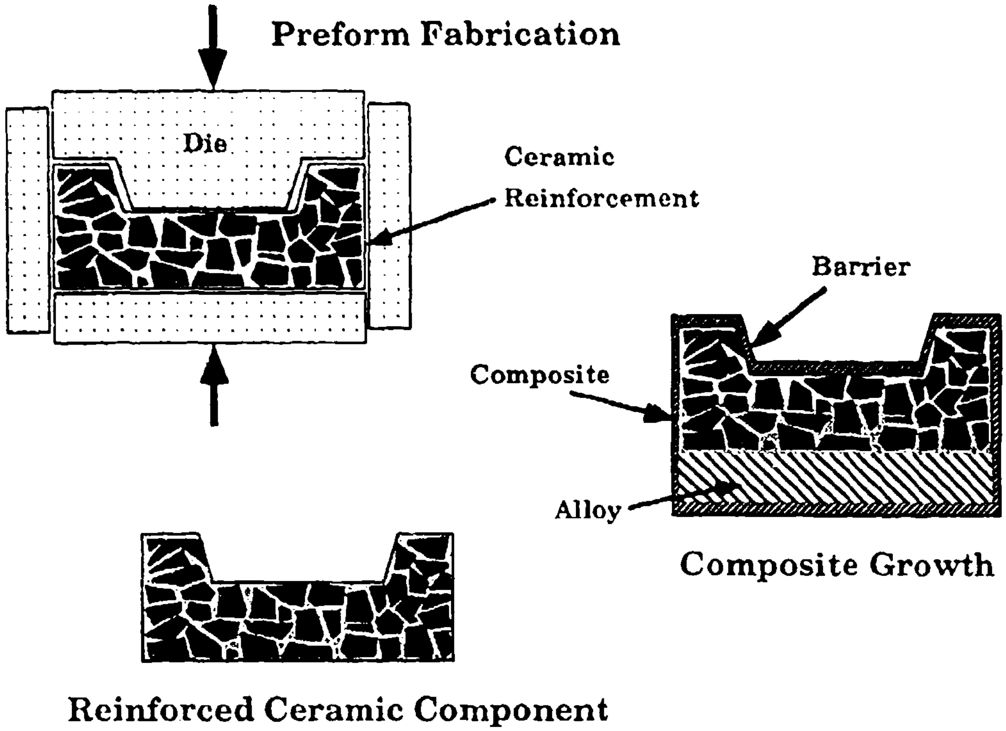


Figure 1. The DIMOX® Directed Metal Oxidation Process.

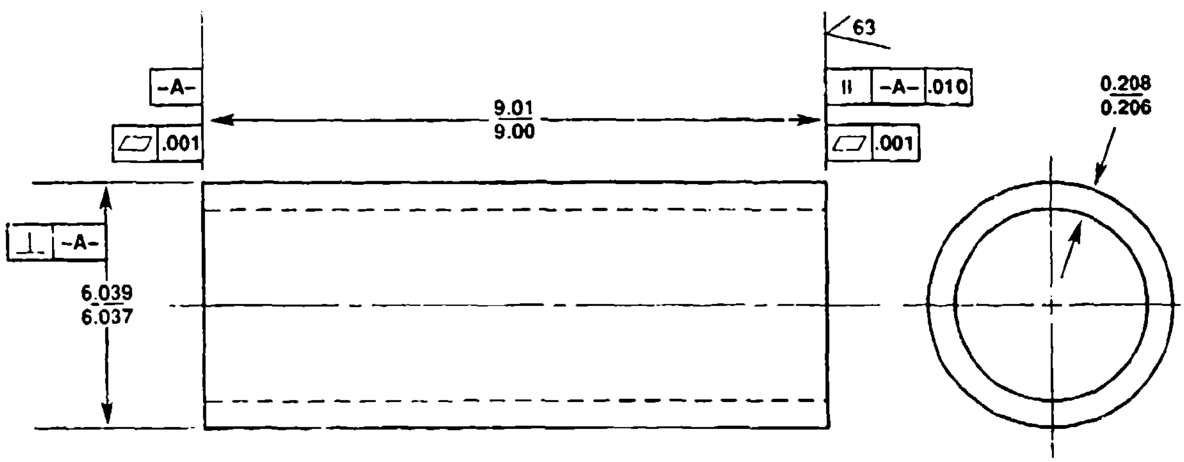


Figure 2. Dimensions of the model scale cylindrical pressure housings.

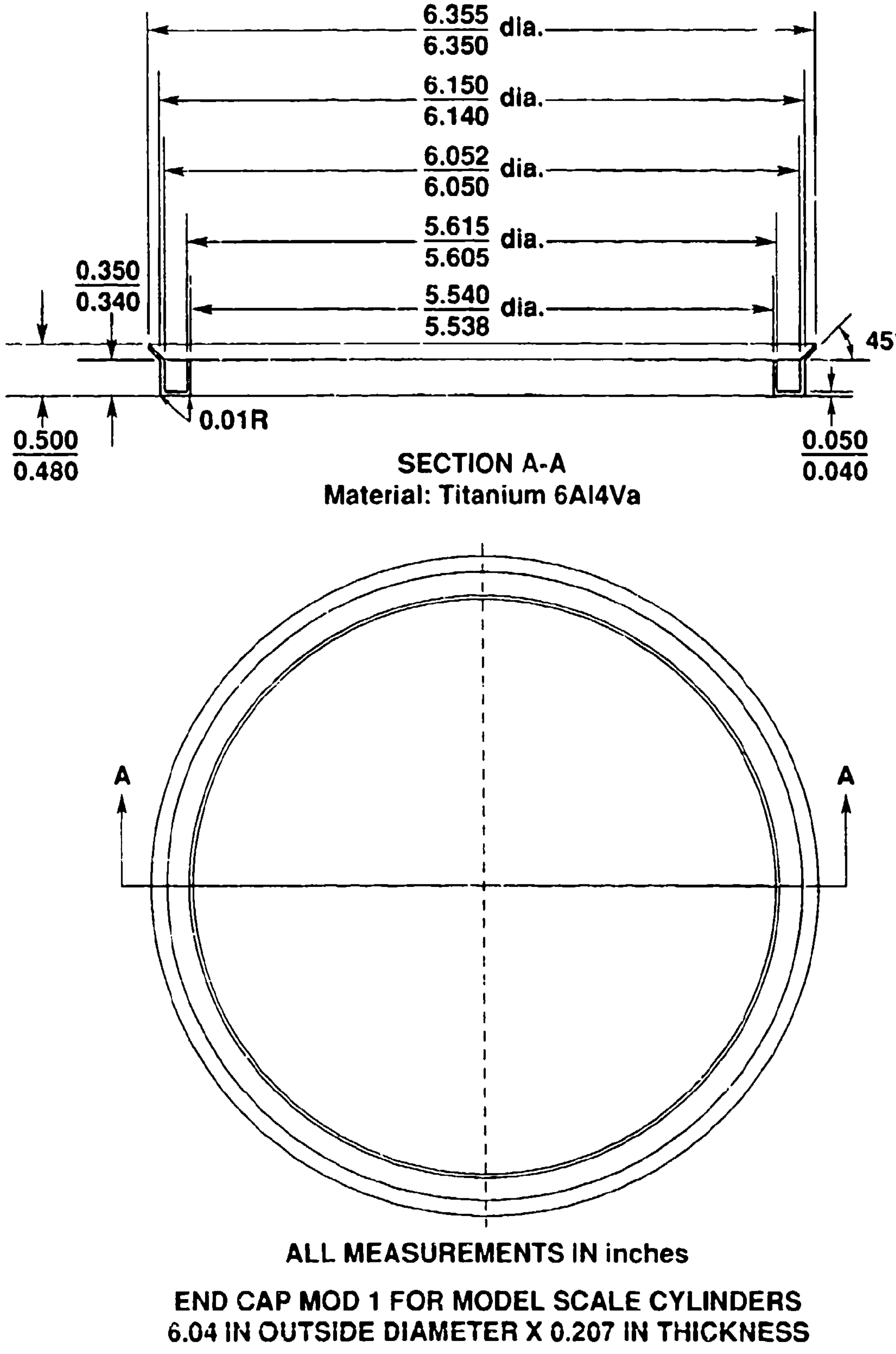


Figure 3. Titanium end caps for protecting the ends of cylinders against spalling.

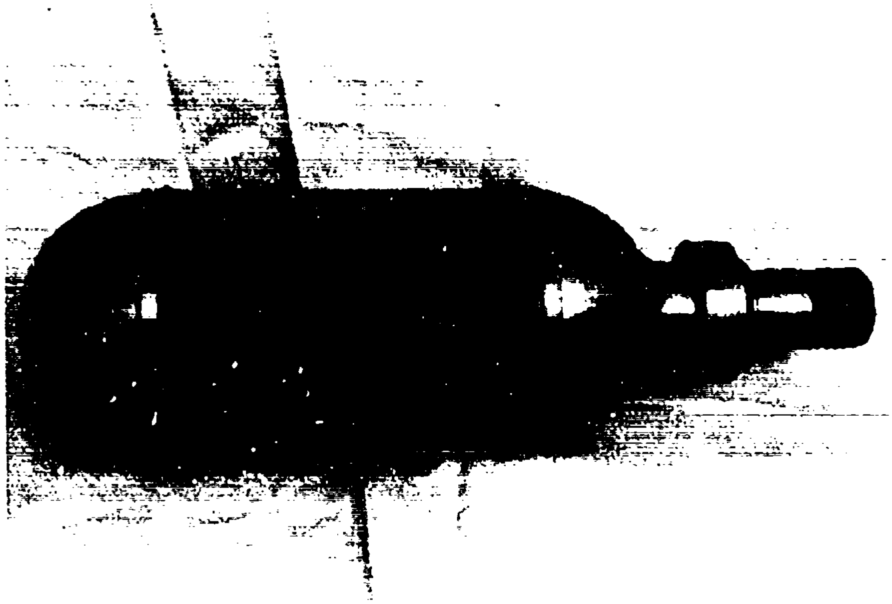


Figure 4. Components of the model scale ceramic pressure housing used in pressure cycling tests.

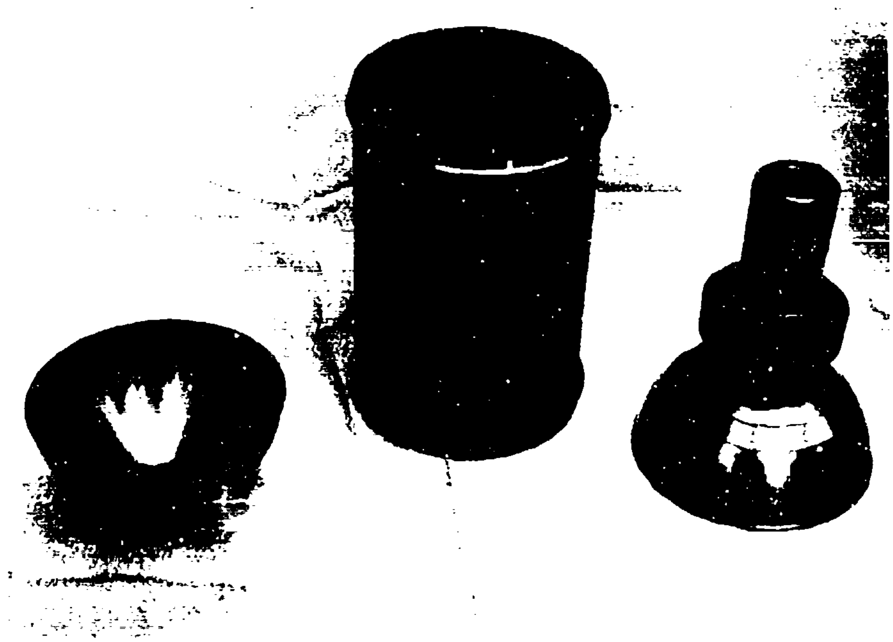


Figure 5. Model scale ceramic housing assembly used for pressure cycling tests. The threaded plug screws into the pressure vessel cover.

Figure 6. Components of the model scale ceramic pressure housing used in implosion testing.

Figure 7. Model scale ceramic housing assembly used in implosion testing of the cylinders.

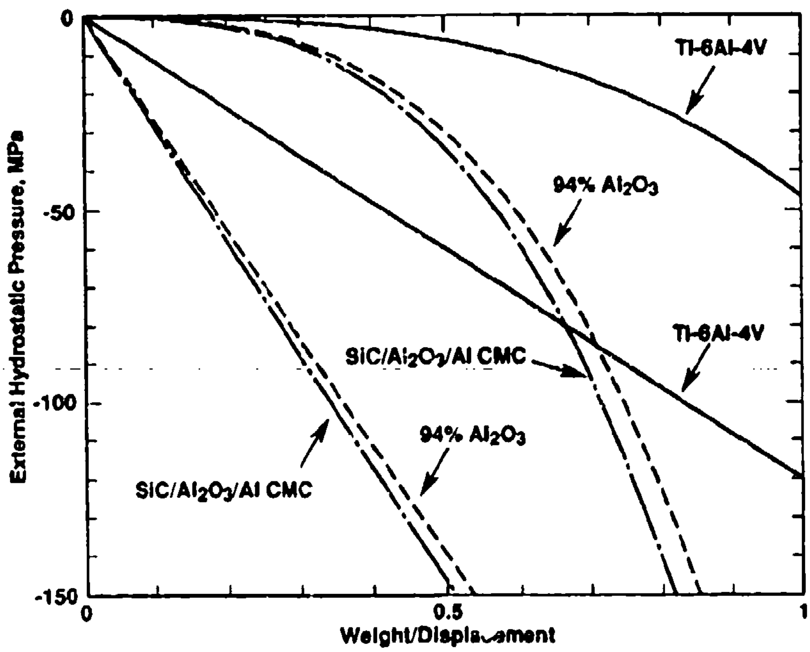


Figure 8. Weight-to-displacement of cylindrical housings from different materials. The straight lines describe material failure of short end-supported cylinders. The curved lines describe buckling failure of long, end-supported cylinders.

Table 1. Comparison of mechanical properties of LANXIDE® 90-X-089 SiC filled Al_2O_3 composite, 94% alumina ceramic and Ti-6Al-4V alloy.

Property	LANXIDE® 90-X-089 SiC Reinforced Al_2O_3 Composite	94 Percent Alumina-Ceramic	Ti-6Al-4V Alloy
Flexural Strength, MPa	359	352	862
($X10^3$ psi)	(52)	(51)	(125)
Compressive Strength, MPa	1952	2103	1070*
($X10^3$ psi)	(283)	(305)	(155)
Density g/cm^3	3.40	3.62	4.43
(lb/ft^3)	(212)	(226)	(227)
Elastic Modulus, GPa	286	310	117
($X10^6$ psi)	(43)	(45)	(17)
Fracture Toughness, $MPa{\cdot}m^{1/2}$	5.3	3.5	—
($ksi{\cdot}in^{1/2}$)	(5.8)	(3.8)	—
Thermal Conductivity, W/m·K	105	18	9
(BTU/hr·Ft·°F)	(60.5)	(10.4)	(5.2)
Poisson Ratio	0.23	0.21	0.3

*Compressive yield stress

Table 2. Structural performance of model scale cylinders under external pressurization.

Model Designation	A (SN 01)	B (SN 02)	C (SN 03)	D (SN 04)	E (SN 05)
Dimensions					
Outside Diameter (in.)	6.036	6.033	6.018	6.005	6.038
Wall Thickness (in.)	0.206	0.207	0.200	0.190	0.208
Length (in.)	9.01	9.01	9.01	7.513	9.010
Weight (gm)	1920	1890	1854	1446	1907
Critical Pressure (psi)	▮ 17,400	▮ 16,000	▮ 16,400	▮ 16,800	22,460*
Nominal Hoop Stress at Implosion (psi)	254,918◆	233,160◆	246,738◆	265,484◆	325,993▼
Pressurizations Prior to Implosion (psi)					
1st	▮ 14,500	—	◗ 10,000	▮ 15,000	◗ 10,000
2nd	▮ 17,300	—	◗ 10,000	▮ 10,000	◗ 10,000
3rd	—	—	◗ 10,000	—	◗ 10,000
4th	—	—	◗ 10,000	—	◗ 10,000
100 cycles	—	—	—	—	◗ 9,000
100 cycles	—	—	—	—	▮ 13,500
100 cycles					▮ 15,000
1 cycle	—	—	—	—	▮ 21,000
Average Hoop/Axial Strains at 10,000 psi					
1st test	—	-3568/-1058	-3681/-1060	-3553/-1080	-3208/-1040
2nd test	—	—	-3473/-1037	-3468/-1058	-3031/-936
3rd test	--	—	-3472/-1034	-3391/-1036	-3029/-939
After 100 cycles to 9,000 psi	—	—	—	—	-3015/-938
After 100 cycls to 13,500 psi	—	—	—	—	-2995/-935
After 100 cycles to 15,000 psi					-2935/-920
Permanent Hoop Strain Set After Pressurizations					
1st test	—	—	-204	-119	-168
2nd test	—	—	-30	-4	+4
3rd test	—	—	-21	+9	+9
After 100 cycles to 9,000 psi	—	—	—	—	-1
After 100 cycles to 13,500 psi	—	—	—	—	+1
After 100 cycles to 15,000 psi					+3

Fabricator: LANXIDE Corporation

Material: Composition 90-X-89 (Al_2O_3/Al matrix reinforced with 500 grit SiC)

End Closures: ◗ Titanium hemispheres providing radial support
▮ Plane bulkheads providing radial support

Strains: All strains are in microinches per inch
Residual strains were zeroed out after each pressurization

Cylinders: 6.03 inch outside diameter x 0.208 inches thick x 9.0 inches long
* Cylinder E has been shortened by 3 inches after cyclic loading but prior to implosion testing

Test Results: ◆ Catastrophic implosion by elastic instability
▼ Catastrophic implosion by material failure

Table 3. Results of cyclic uniaxial compression testing of 94% alumina and SIC/AL_2O_3 composite.

Test 1. Regular Cylinder (9.5mm dia x 19mm long)

Material	Maximum Stress GPa (ksi)	No. of Cycles	Comments
96% Al_2O_3	-1.0 (-145)	10,190	7 mm longitudinal crack propagated from end
	-1.0 (-148)	+2000	Original crack extended to 8.5mm. New 2.3mm cracks initiated
90-X-089	-1.0 (-145)	10,000	No cracks
	-1.5 (-218)	+ 26,680	Specimen failed

Test 2. Indented Cylinder Ends (9.5mm dia x 19mm long)

Material	Maximum Stress GPa (ksi)	No. of Cycles	Comments
96% Al_2O_3	-1.0 (-145)	10	2.3 mm longitudinal crack propagated from end (Not from indent)
	-1.0 (-145)	+90	Crack extended to 6.6 mm
90-X-089	-1.0 (-145)	10,000	No cracks. Indentation fretted
	-1.0 (-145)	+10,000	No cracks

APPENDIX A
TEST DATA FROM PRESSURE TESTING OF 6-INCH DIAMETER CYLINDERS FABRICATED BY THE LANXIDE® CORPORATION FROM ALUMINA CERAMIC COMPOSITE 90-X-089

INTRODUCTION

Due to limitations imposed by the Marine Technology Society on the length of the paper for inclusion in the Proceedings of the Intervention/ROV 91 Conference, all of the data generated during the test program could not be included. These data have been collected and, together with some discussion, have been incorporated into Appendix A.

DISCUSSION

The critical pressures in the range of 16,000 to 17,400 psi of 6-inch × 9-inch L × 0.27-inch thick cylinders simply supported at the ends are the result of elastic instability, and not the result of material failure. This is supported by the fact that cylinder E (SNO5), after being shortened from 9 to 6 inches (i.e., from L/D = 1.5 to 1.0), successfully withstood pressurization to 21,000 psi, and failed only after the pressure was increased to 22,460 psi. Based on the magnitude of strains recorded on the interior surfaces of cylinders, the modulus of elasticity under biaxial compression of LANXIDE® 90-X-089 composite is calculated to vary between 40 to 45 × 10^6 psi. This range of values is supported by uniaxial compression tests performed on solid-cylinder test specimens.

The compression strength of LANXIDE® 90-X-089 composite under biaxial compression was found to exceed 305,000 psi. The single cylinder, shortened to 6 inches after 100 pressure cycles to 218,000 psi to prevent it from imploding in the 17,500–18,000 psi range due to elastic instability, failed at a stress level of 326,000 psi. This indicates that the biaxial compressive strength of this composite is well in excess of 283,000 psi attained by the testing of the American Society of Testing Materials (ASTM) specimens under uniaxial compression.

It is interesting to note that the magnitude of compressive strains decreases with repeated pressurizations until, after approximately 100 pressure cycles, it reaches a constant value. The change in strains is not large, but still significant, indicating a compaction process taking place inside the composite. The magnitude of permanent compaction under biaxial stress level of 150,000 psi is in the range of 0.02 to 0.03 percent. In this respect, the LANXIDE® composite differs significantly from alumina ceramics, which show *no compaction* during compressive stress loading in the same stress range.

The number of acoustic events recorded during the first pressure testing of LANXIDE® composite cylinders was significantly less than for alumina ceramic. During succeeding pressurizations, there was a total absence of acoustic emissions, as compared to a small number observed during repeated pressurizations of alumina ceramic cylinders.

Only a single spall was observed on the plane-bearing surface of cylinder E (SNO5). The spall appeared on the exterior surface after a total of 300 pressure cycles (100 cycles to stress level of 131,000 psi, 100 cycles to 196,000 psi, and 100 cycles to 218,000 psi). In general, the composite appeared to be more resistant to spalling on the bearing surface than was alumina ceramic under the same test conditions.

FINDINGS

1. The mechanical properties of LANXIDE® composite 90-X-089 are equal to those of 94-percent alumina ceramic. The composite is superior to 94-percent alumina ceramic in that its thermal conductivity and fracture toughness are higher and its density is less than that found in alumina ceramic.
2. The actual weight-to-displacement ratio of cylindrical housings fabricated from

LANXIDE® composite is 5 to 10 percent less than that of identical housings fabricated from 94-percent alumina ceramic. Equipped with titanium end rings, cylindrical housings that were designed with a safety factor of two, based on both the elastic stability and material strength, have a weight-to-displacement ratio that falls into the 0.45 to 0.47 range.

FIGURES AND TABLES

The tables and graphic plots depict the performance of LANXIDE® 90-X-089 ceramic composite and the housing fabricated from it under compressive loading.

The data generated by hydrostatic testing of each ceramic composite cylinder (except for cylinder SN01) is presented in both tabular and graphic formats. The tables present the strains on the interior surface of cylinders both at midbay and at the ends near radial support by the end closures. The graphs show only the strains at midbay and the acoustic emissions generated by the whole housing.

The data resulting from the cyclic uniaxial compression test of a small cylindrical test specimen is displayed graphically as axial and transverse strains versus stress. On the basis of these strains the Poisson's ratio has been calculated to be 0.23. This ratio remains constant through the range of stresses from 0 to 280,000 psi.

The drawings describe the two types of end closures used during testing of the 6-inch diameter cylinders. The hemispherical end closures were used only on cylinders C and E during pressure cycling in the 0 to 10,000 psi range. For testing at higher pressures, the hemispherical end closures were replaced with aluminum or steel flat bulkheads capable of withstanding higher pressures. Needless to say, the flat bulkheads provided stiffer radial support than hemispherical bulkheads, which caused higher flexure moments near the supports.

The photographs depict the gun barrel used for pressure testing of the cylinders, as well as the results of these tests. The destructive testing resulted every time in fine fragments except in the case of cylinder (SN01), which had a wooden plug filling the whole interior of the housing. Because the annular space between the wooden plug and the ceramic cylinder was only 0.25 inch, the ceramic did not have the chance to shatter into fine fragments. The long fragments, resembling the staves of a barrel, were generated by formation of many buckling lobes on the surface of the cylinder during implosion at 17,400 psi.

One of the photographs shows the spalling of exterior surface on cylinder E (SN05) after it was subjected to 300 pressure cycles. In appearance, the spall was identical to those observed on alumina ceramic cylinders after extensive pressure cycling. The depth of spall was less than 0.030 inch.

PERFORMANCE OF LANXIDE® CERAMIC CYLINDER A (SN#1)

Composition:	LANXIDE® 90-X-089 SiC particulate reinforced alumina ceramic.
Cylinder Dimensions:	6.036 inches OD × 5.624 inches ID × 9.0 inches L × 0.206 inch thick.
Cylinder Weight:	1920 grams.
Defects:	0.032 inch deep pit on external surface at midbay.
End Closures:	Plane bulkheads providing radial and axial support.
Critical Pressure:	The cylinder imploded at 17,400 psi during short-term pressurization.

Cylinder B

Strains on LANXIDE™ ceramic cylinder B (SN# 02) under short term pressurization

Gage Locations

	|<------ Interior Midbay											------>|	|<----- Interior End ----->|	
Pressure	A		B		C		D		E		F		G	
(Psi)	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	-282	-156	-357	-47	-345	-112	-266	-162	-376	-46	-321	-107	210	-5482
2000	-578	-287	-740	-115	-684	-206	-567	-305	-752	-120	-657	-206	444	-4503
3000	-910	-386	-1112	-215	-1045	-311	-914	-424	-1116	-227	-1013	-318	620	-4054
4000	-1240	-482	-1489	-319	-1412	-415	-1269	-541	-1480	-335	-1379	-435	815	-3792
5000	-1557	-570	1854	-419	-1769	-517	-1615	-655	-1832	-440	-1736	-547	949	-3624
6000	-1915	-665	-2247	-528	-2168	-629	-1992	-777	-2224	-556	-2123	-670	1038	-3477
7000	-2261	-754	-2625	-630	-2551	-736	-2352	-894	-2600	-665	-2491	-785	1119	-3376
8000	-2590	-836	-2995	-730	-2919	-839	-2701	-1005	-2966	-772	-2849	-899	1188	-3296
9000	-2935	-920	-3381	-832	-3299	-846	-3065	-1120	-3346	-881	-3219	-1015	1261	-3227
10000	-3269	-991	-3758	-931	-3668	-1048	-3420	-1230	-3716	-987	-3577	-1127	1382	-3148
11000	-3623	-1077	-4155	-1036	-4059	-1157	-3796	-1349	-4115	-1101	-3958	-1248	1526	-3027
12000	-3963	-1148	-4526	-1134	-4427	-1258	-4149	-1460	-4494	-1206	-4307	-1358	1644	-2905
13000	-4320	-1211	-4903	-1235	-4811	-1360	-4510	-1572	-4893	-1312	-4657	-1474	1744	-2722
14000	-4676	-1242	-5260	-1338	-5200	-1460	-4854	-1688	-5311	-1416	-4974	-1589	693	-2100
15000	-5131	-1285	-5557	-1456	-5672	-1549	-5145	-1813	-5822	-1508	-5198	-1718	709	-1856
16000									-7546	-8778				

NOTES: Specimen imploded at 16,000 psi

All strains are in microinches per inch

Electric resistance strain gages are CEA-06-125WT-350, Gage Factor 2.09

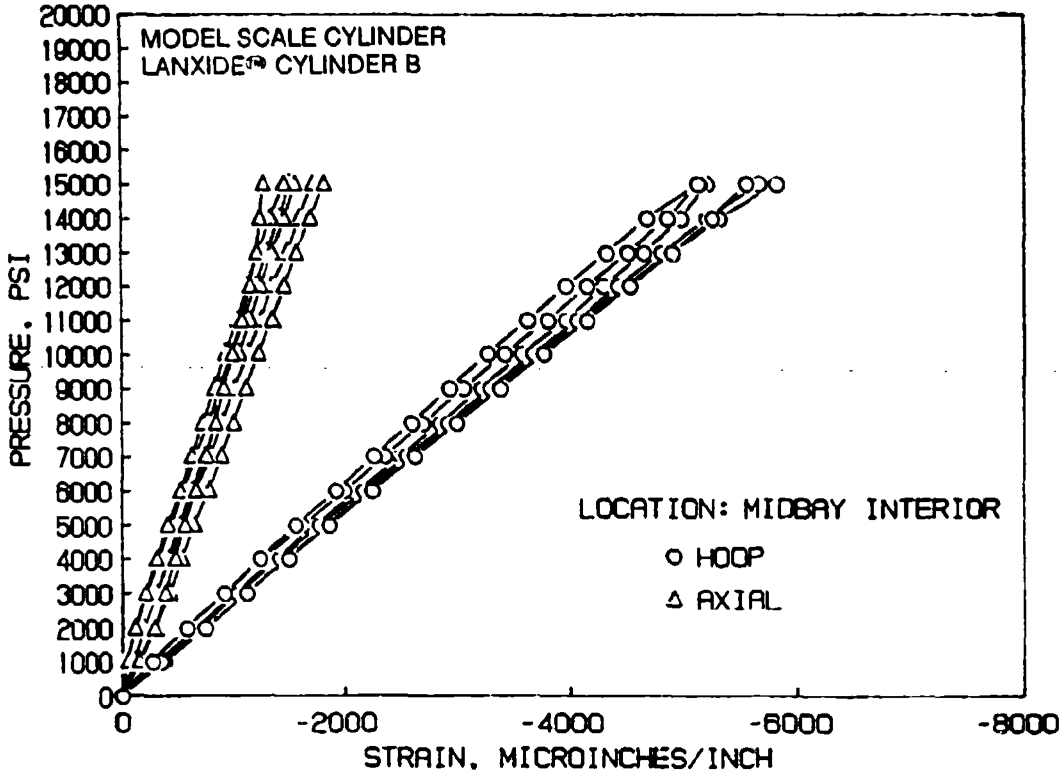
Ceramic Composition: Lanxide 90-X-89, SiC particulate reinforced alumina ceramic

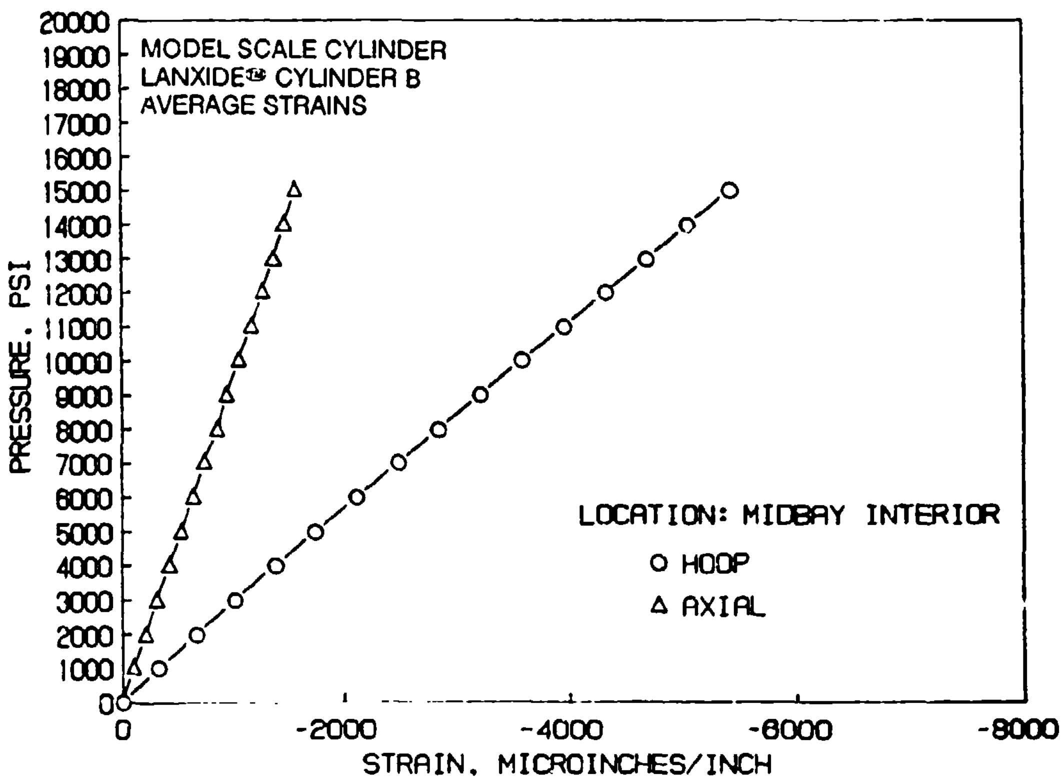
End Closures: Plane Bulkheads providing radial and axial support

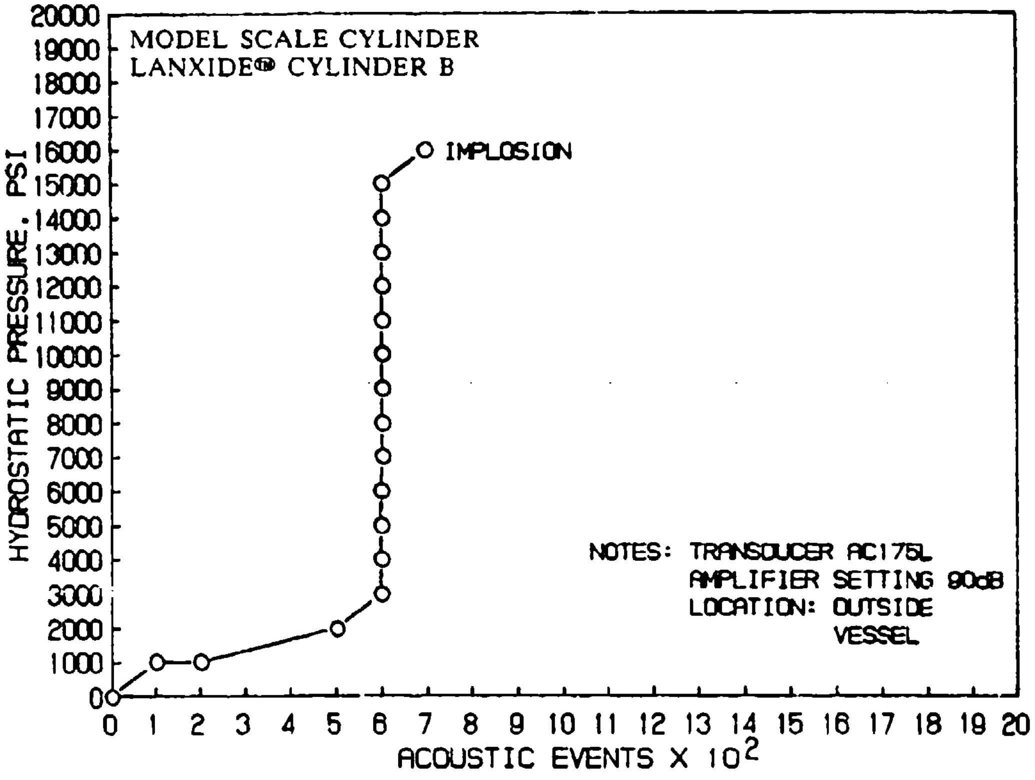
Cylinder Dimensions: 6.033 in OD x 5.619 in ID x 9.01 in L x 0.207 in thick

Cylinder Weight: 1890 grams

Quality: Metal rich areas observed on cylinder surface


MODEL SCALE CYLINDER
LANXIDE™ CYLINDER B
LOCATION: MIDBAY INTERIOR
O HOOP
Δ AXIAL
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
0
-2000
-4000
-6000
-8000


MODEL SCALE CYLINDER
LANXIDE™ CYLINDER B
AVERAGE STRAINS
LOCATION: MIDBAY INTERIOR
O HOOP
Δ AXIAL
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
0
-2000
-4000
-6000
-8000



MODEL SCALE CYLINDER
LANXIDE® CYLINDER B
IMPLOSION
NOTES: TRANSDUCER AC175L
AMPLIFIER SETTING 90dB
LOCATION: OUTSIDE
VESSEL
HYDROSTATIC PRESSURE, PSI
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
ACOUSTIC EVENTS X 10²

Cylinder C

Strains on LANXIDE® ceramic cylinder C (SN# 03) under short term pressurization
Pressurizations No. 1 & 2

Gage Locations

|<------ Interior Midbay ------>|<--- Interior End --->|

Pressure (Psi)	1 Hoop	1 Axial	2 Hoop	2 Axial	3 Hoop	3 Axial	4 Hoop	4 Axial	5 Hoop	5 Axial	6 Hoop	6 Axial
0	0	0	0	0	0	0	0	0	0	0	0	0
1000	-318	-96	-325	-101	-297	-98	-337	-108	-303	-94	-309	
2000	-657	-203	-663	-208	-633	-208	-678	-215	-642	-203	-629	
3000	-1019	-304	-1024	-312	-993	-316	-1043	-319	-1003	-309	-964	
4000	-1387	-407	-1391	-416	-1360	-424	-1415	-422	-1369	-416	-1303	
5000	-1770	-516	-1770	-526	-1739	-539	-1799	-532	-1745	-530	-1655	
6000	-2154	-618	-2147	-631	-2117	-650	-2184	-636	-2119	-641	-2006	
7000	-2545	-723	-2522	-737	-2501	-760	-2571	-739	-2494	-754	-2357	
8000	-2944	-826	-2898	-844	-2892	-872	-2960	-841	-2869	-866	-2709	
9000	-3358	-925	-3267	-953	-3307	-983	-3348	-942	-3253	-984	-3075	
10000	-3781	-1013	-3555	-1066	-3774	-1083	-3665	-1040	-3633	-1100	-3435	
0	-226	-25	-204	-33	-206	-36	-217	-37	-199	-32	-174	
1000	-320	-97	-324	-100	-299	-98	-339	-105	-296	-96	-329	
2000	-643	-198	-643	-201	-621	-203	-662	-206	-613	-199	-631	
3000	-981	-302	-975	-306	-956	-310	-1000	-310	-944	-307	-944	
4000	-1332	-407	-1319	-412	-1304	-420	-1350	-414	-1287	-417	-1271	
5000	-1637	-495	-1614	-502	-1605	-513	-1652	-502	-1582	-511	-1549	
6000	-2009	-598	-1971	-609	-1973	-623	-2021	-606	-1943	-622	-1887	
7000	-2382	-699	-2325	-714	-2343	-731	-2388	-707	-2301	-733	-2223	
8000	-2769	-798	-2684	-821	-2726	-840	-2761	-806	-2667	-846	-2568	
9000	-3175	-897	-3042	-931	-3135	-952	-3138	-906	-3046	-964	-2928	
10000	-3572	-986	-3339	-1041	-3577	-1054	-3449	-1002	-3427	-1078	-3272	
0	-37	-7	-32	-10	-24	-4	-36	-4	-21	-5		

NOTES: Test Terminated at 10,000 psi, no implosion
All strains are in microinches per inch, gages were re-zeroed between pressurizations
Electric resistance strain gages are CEA-03-125WT-350, Gage Factor 2.09
Ceramic Composition: Lanxide 90-X-89, SiC particulate reinforced alumina ceramic
End Closures: Titanium Hemispherical Bulkheads providing radial support
Cylinder Dimensions: 6.018 OD x 5.619 ID x 9.010 L x 0.200 in thick
Cylinder Weight: 1854 grams
Quality: Visual observation did not disclose any defects

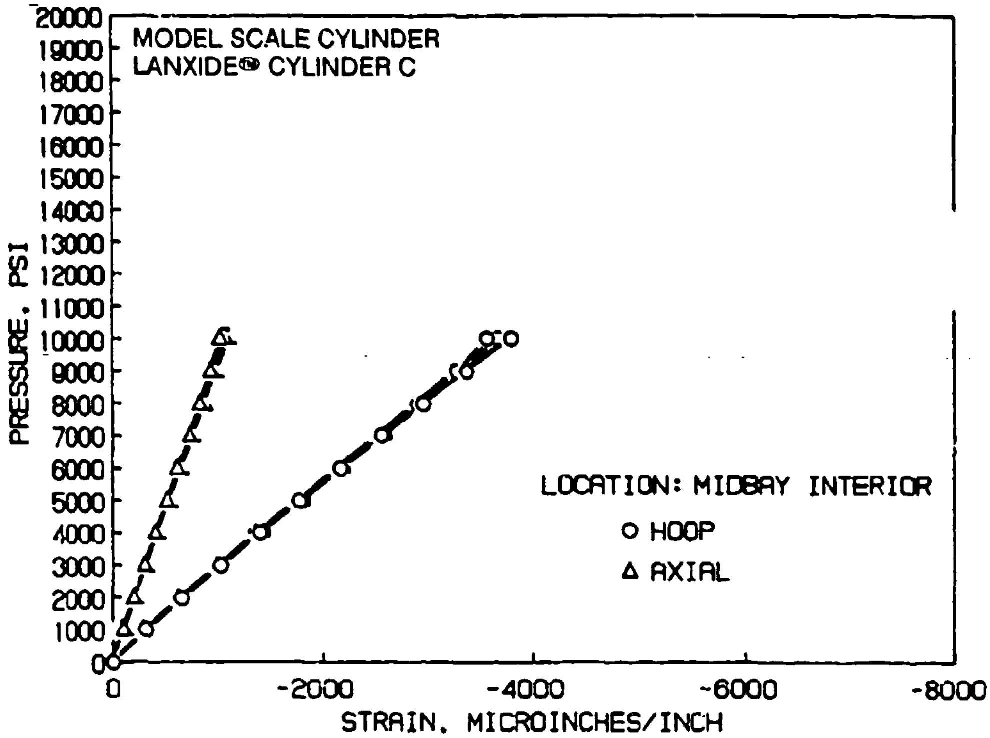
Cylinder C

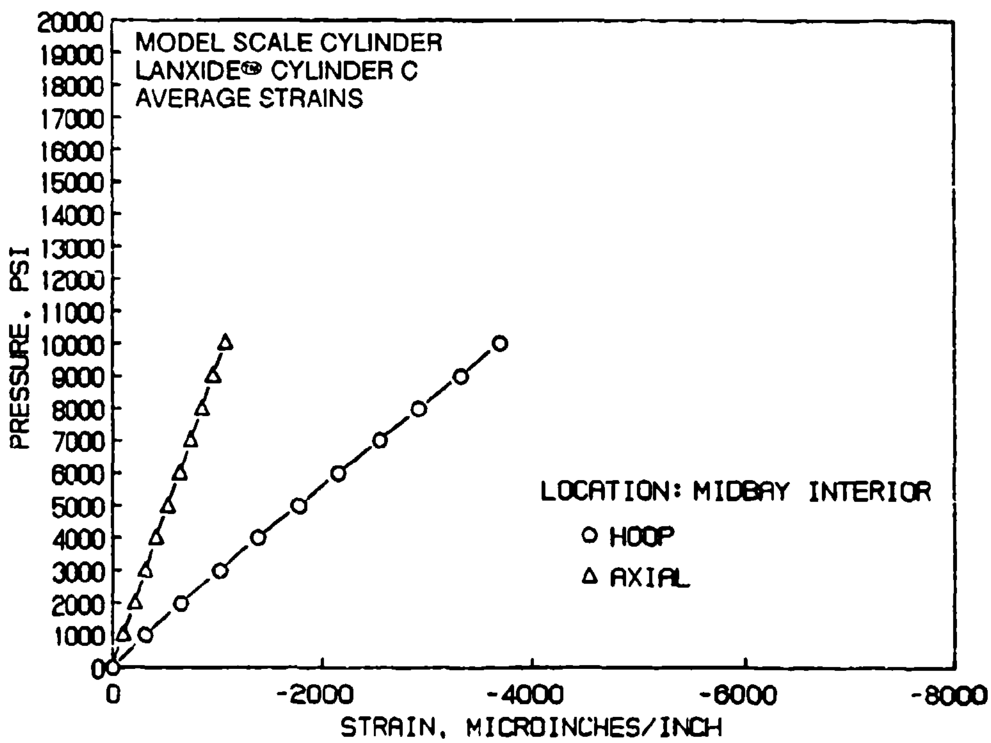
Strains on LANXIDE® ceramic cylinder C (SN# 03) under short term pressurization
Pressurizations No. 3 & 4

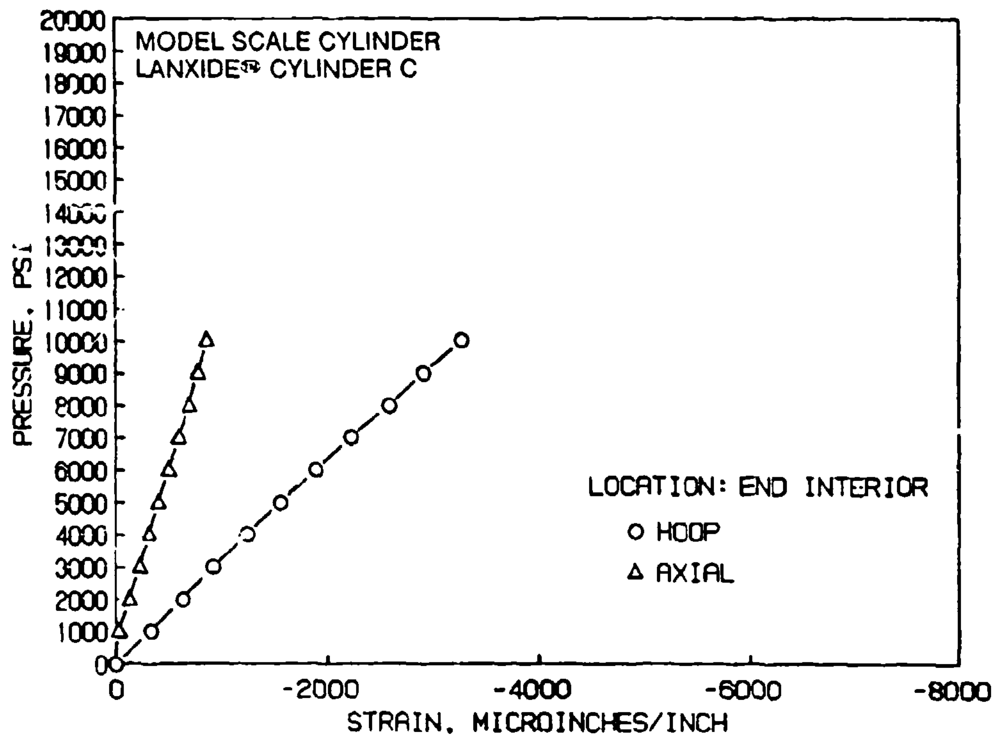
Gage Locations

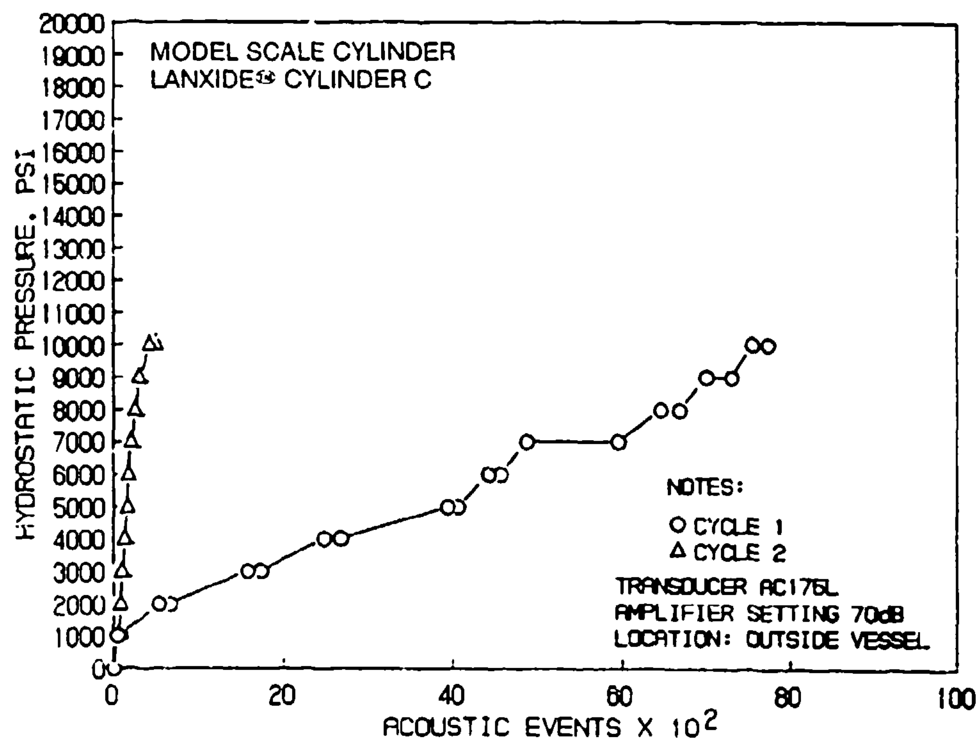
Pressure	Interior Midbay										Interior End	
	1		2		3		4		5		6	
(Psi)	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial
0	0	0	0	0	0	0	0	0	0	0	0	0
1000	-324	-101	-319	-97	-299	-97	-343	-107	-288	-99	-320	-30
2000	-653	-202	-639	-199	-622	-202	-667	-209	-607	-204	-624	-128
3000	-961	-298	-945	-298	-930	-302	-978	-305	-912	-304	-914	-221
4000	-1300	-400	-1277	-401	-1268	-409	-1317	-408	-1244	-411	-1229	-314
5000	-1647	-500	-1511	-503	-1608	-513	-1658	-507	-1578	-516	-1546	-404
6000	-2016	-603	-1967	-610	-1975	-624	-2025	-610	-1937	-628	-1881	-501
7000	-2388	-703	-2318	-714	-2342	-732	-2388	-709	-2291	-737	-2212	-592
8000	-2787	-804	-2688	-825	-2739	-845	-2772	-812	-2670	-854	-2569	-687
9000	-3169	-897	-3025	-929	-3126	-950	-3125	-906	-3030	-965	-2908	-772
10000	-3576	-987	-3332	-1042	-3585	-1054	-3441	-1006	-3427	-1083	-3264	-857
0	-28	-2	-17	-1	-21	-1	-24	-4	-14	-2	-16	0
1000	-327	-103	-328	-101	-300	-98	-343	-105	-296	-103	-332	-28
2000	-646	-202	-644	-200	-620	-201	-663	-205	-612	-206	-632	-125
3000	-968	-301	-963	-302	-940	-305	-987	-305	-928	-310	-936	-220
4000	-1308	-403	-1292	-405	-1276	-411	-1324	-406	-1258	-416	-1244	-308
5000	-1657	-503	-1628	-508	-1620	-516	-1668	-507	-1595	-523	-1566	-398
6000	-2019	-603	-1978	-612	-1981	-624	-2029	-607	-1948	-631	-1894	-491
7000	-2390	-702	-2327	-716	-2346	-731	-2388	-706	-2300	-744	-2224	-584
8000	-2778	-804	-2690	-827	-2734	-844	-2763	-808	-2670	-857	-2570	-674
9000	-3186	-904	-3049	-939	-3150	-957	-3139	-909	-3057	-977	-2930	-766
10000	-3571	-990	-3338	-1047	-3589	-1055	-3433	-1006	-3438	-1088	-3263	-844
0	-16	6	-16	6	-7	8	-10	8	-12	3	-22	8

NOTES: Test Terminated at 10,000 psi, no implosion
All strains are in microinches per inch, gages were re-zeroed between pressurizations
Electric resistance strain gages are CEA-03-125WT-350, Gage Factor 2.09
Ceramic Composition: Lanxide 90-X-89, SiC particulate reinforced alumina ceramic
End Closures: Titanium Hemispherical Bulkheads providing radial support
Cylinder Dimensions: 6.018 OD x 5.619 ID x 9.010 L x 0.200 in thick
Cylinder Weight: 1854 grams
Quality: Visual observation did not disclose any defects


MODEL SCALE CYLINDER
LANXIDE® CYLINDER C
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
LOCATION: MIDBAY INTERIOR
HOOP
AXIAL


MODEL SCALE CYLINDER
LANXIDE® CYLINDER C
AVERAGE STRAINS
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
LOCATION: MIDBAY INTERIOR
HOOP
AXIAL


MODEL SCALE CYLINDER
LANXIDE® CYLINDER C
LOCATION: END INTERIOR
O HOOP
Δ AXIAL
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
-2000
-4000
-6000
-8000


MODEL SCALE CYLINDER
LANXIDE® CYLINDER C
NOTES:
O CYCLE 1
Δ CYCLE 2
TRANSDUCER AC175L
AMPLIFIER SETTING 70dB
LOCATION: OUTSIDE VESSEL
HYDROSTATIC PRESSURE, PSI
ACOUSTIC EVENTS X 10²
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100

Cylinder D

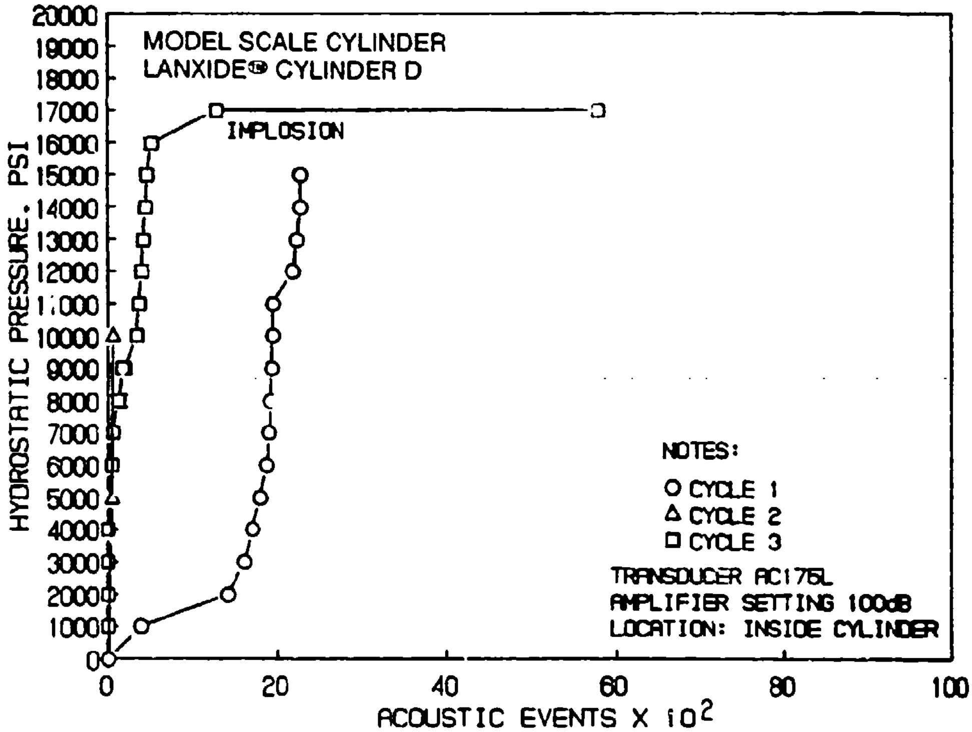
Strains on LANXIDE® ceramic cylinder D (SN# 04) under short term pressurization

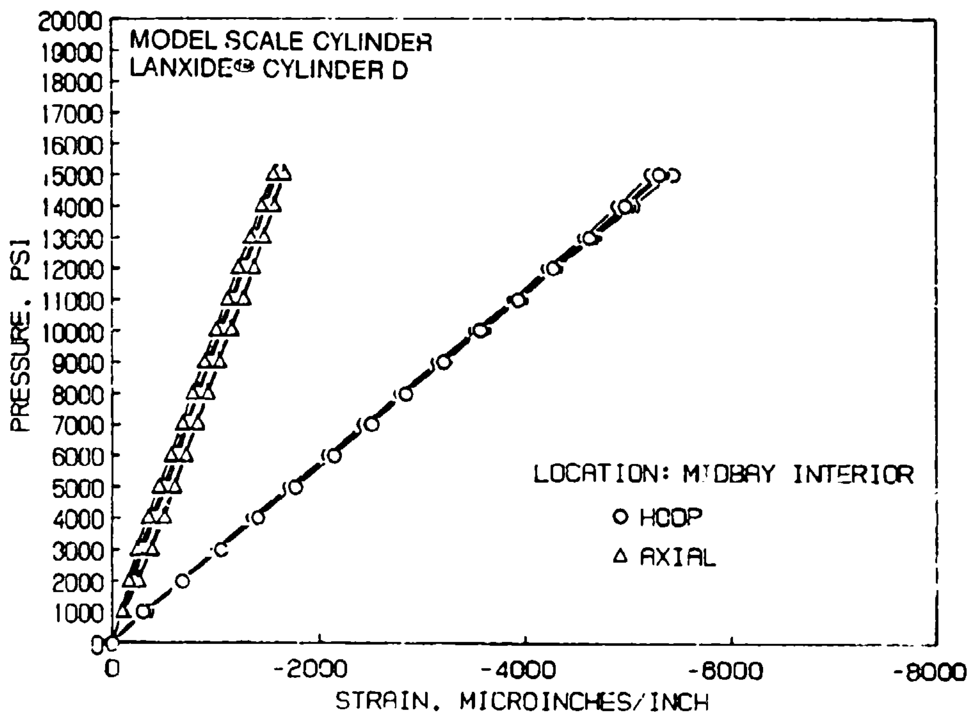
Gage Locations

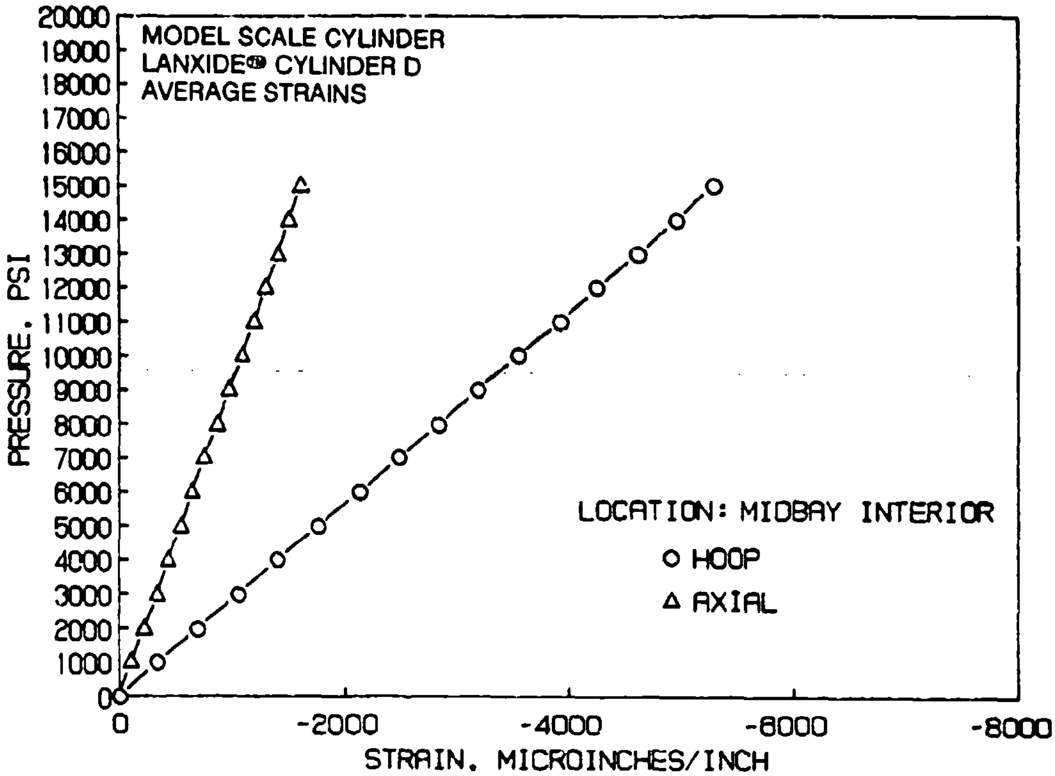
|<------------------------------ Interior Midbay ------------------------------>|<--------- Interior Ends --------->|

Pressure (Psi)	A Hoop	A Axial	B Hoop	B Axial	C Hoop	C Axial	D Hoop	D Axial	E Hoop	E Axial	F Hoop	F Axial	G Hoop	G Axial
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	-302	-97	-338	-112	-307	-99	-313	-104	-338	-115	-38	320	22	317
2000	-675	-164	-670	-267	-693	-185	-692	-208	-688	-249	-246	288	-197	436
3000	-1057	-240	-1011	-394	-1043	-281	-1050	-312	-1020	-376	-550	317	-505	507
4000	-1409	-345	-1359	-499	-1391	-385	-1399	-416	-1370	-482	-848	93	-797	485
5000	-1773	-452	-1719	-608	-1748	-494	-1764	-525	-1733	-590	-1257	-449	-1098	450
6000	-2147	-564	-2083	-718	-2122	-606	-2128	-635	-2105	-704	-1661	-902	-1358	392
7000	-2505	-673	-2449	-827	-2477	-716	-2496	-742	-2471	-813	-1840	-956	-1549	295
8000	-2849	-779	-2800	-934	-2820	-822	-2852	-846	-2824	-920	-2007	-978	-1722	197
9000	-3211	-891	-3165	-1043	-3180	-933	-3221	-956	-3196	-1032	-2161	-841	-1904	92
10000	-3566	-1001	-3522	-1151	-3533	-1043	-3580	-1064	-3565	-1142	-2223	-810	-2086	-6
11000	-3931	-1116	-3887	-1261	-3896	-1156	-3949	-1176	-3942	-1253	-2357	-834	-2279	-83
12000	-4265	-1220	-4213	-1362	-4222	-1259	-4287	-1278	-4291	-1355	-2496	-857	-2466	-130
13000	-4619	-1333	-4561	-1466	-4569	-1369	-4645	-1386	-4667	-1461	-2678	-848	-2675	-154
14000	-4956	-1441	-4891	-1565	-4895	-1474	-4987	-1490	-5037	-1561	-2890	-805	-2881	-137
15000	-5291	-1551	-5212	-1662	-5217	-1580	-5326	-1593	-5424	-1659	-3079	-764	-3091	449
10000	-3668	-1020	-3607	-1122	-3592	-1040	-3660	-1041	-3742	-1133	-2477	-344	-2306	616
5000	-2002	-514	-1960	-618	-1967	-546	-2026	-552	-2005	-615	-1796	-205	-1540	109
0	-104	-20	-123	-22	-111	-26	-119	-18	-140	-27	-635	-447	-12	60
10000	-3429	-1000	-3356	-1109	-3370	-1032	-3441	-1045	-4417	-1103	-2815	-157	-2166	456
5000	-1816	-478	-1748	-584	-1767	-510	-1817	-523	-1777	-572	-1141	123	-1408	83
0	-2	-1	-5	-5	3	-3	-5	-4	-6	0	-59	-20	27	
5000	-1649	-458	-1603	-567	-1648	-481	-1641	-502	-1610	-561				
10000	-3399	-982	-3352	-1090	-3405	-1005	-3409	-1021	-3390	-1084				
15000	-5113	-1509	-5050	-1592	-5158	-1520	-5118	-1545	-5250	-1579				
0	11	16	-15	16	27	24	-18	16	4	21				

NOTES: Cylinder cracked and filled with water at 16,800 psi
All strains are in microinches per inch
Electric resistance strain gages are CEA-03-125WT-350, Gage Factor 2.12
Ceramic Composition: Lanxide 90-X-89, SiC particulate reinforced alumina ceramic
End Closures: Plane Bulkheads providing radial support
Cylinder Dimensions: 6.005 OD x 5.618 ID x 7.513 L x 0.190 in thick
Cylinder Weight: 1446 grams
Quality: No visually detectable defects


MODEL SCALE CYLINDER
LANXIDE® CYLINDER D
IMPLOSION
NOTES:
O CYCLE 1
Δ CYCLE 2
□ CYCLE 3
TRANSDUCER AC175L
AMPLIFIER SETTING 100dB
LOCATION: INSIDE CYLINDER
HYDROSTATIC PRESSURE, PSI
ACOUSTIC EVENTS X 10^2


MODEL SCALE CYLINDER
LANXIDE® CYLINDER D
LOCATION: MIDBAY INTERIOR
O HOOP
Δ AXIAL
PRESSURE, PSI
STRAIN, MICROINCHES/INCH


MODEL SCALE CYLINDER
LANXIDE® CYLINDER D
AVERAGE STRAINS
LOCATION: MIDBAY INTERIOR
HOOP
AXIAL
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
-2000
-4000
-6000
-8000

Cylinder E

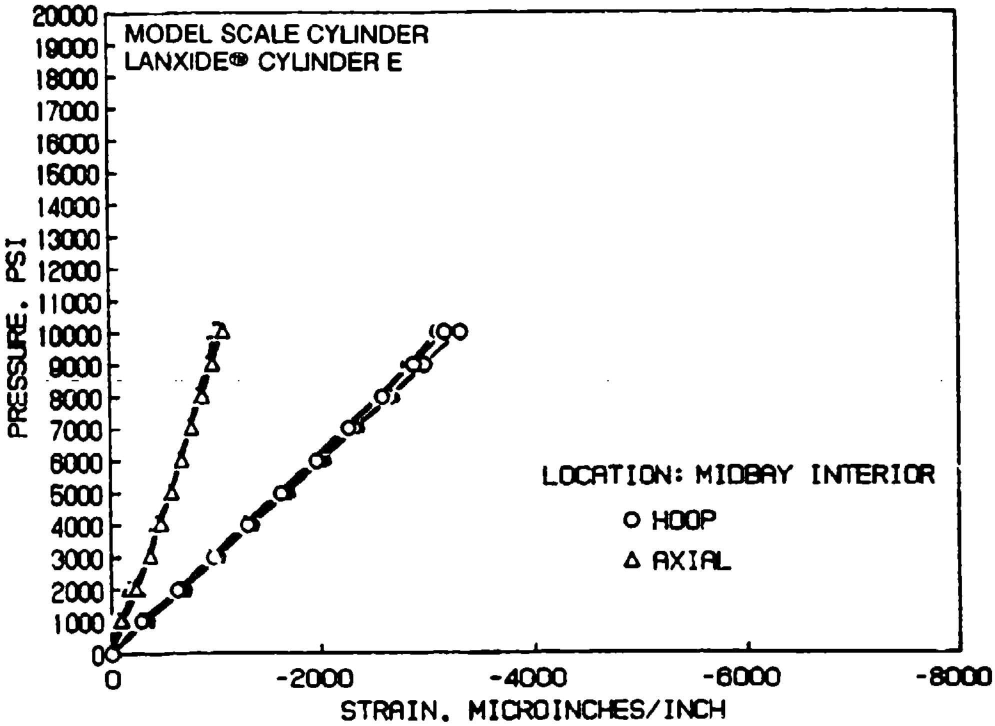
Strains on LANXIDE® ceramic cylinder E (SN# 05) under short term pressurization

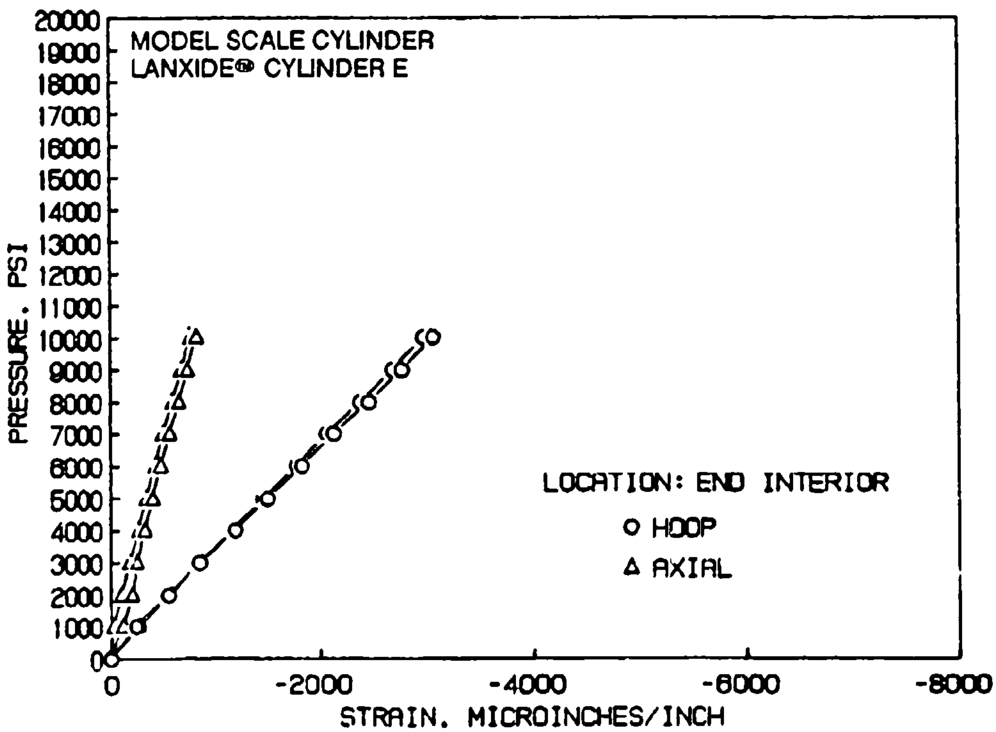
Gage Locations

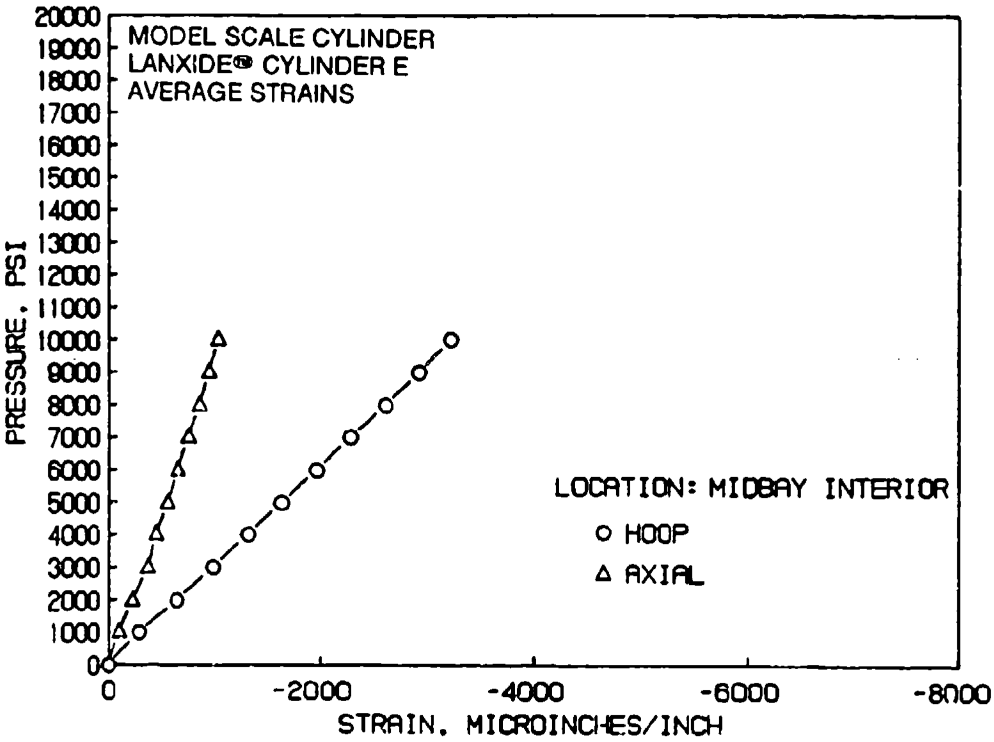
|<------------------------------- Interior Midbay ------------------------------->|<--------- Interior Ends --------->|

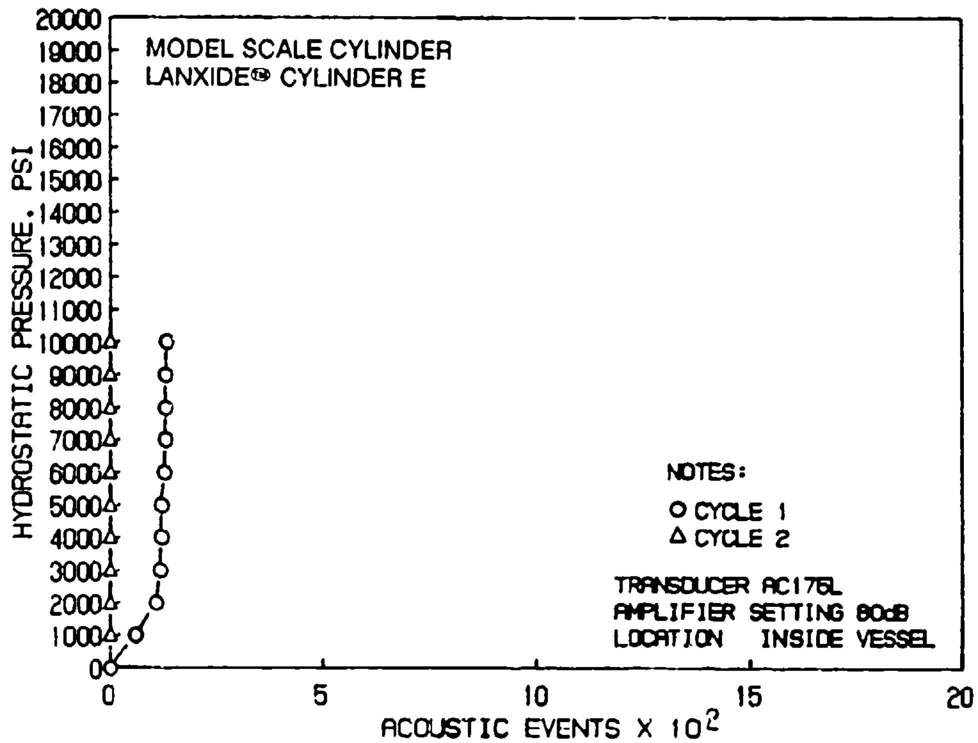
Pressure (Psi)	A Hoop	A Axial	B Hoop	B Axial	C Hoop	C Axial	D Hoop	D Axial	E Hoop	E Axial	F Hoop	F Axial	G Hoop	G Axial
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	-278	-90	-303	-92	-274	-67	-264	-122	-339	-115	-234	-118	-269	-27
2000	-630	-230	-662	-245	-643	-235	-641	-159	-703	-255	547	-196	-564	-105
3000	-979	-370	-1015	-377	-981	-359	-959	-373	-1029	-369	-852	-254	-851	-177
4000	-1307	-471	-1345	-477	-1286	-440	-1263	-457	-1352	-438	-1188	-322	-1169	-262
5000	-1618	-571	-1657	-571	-1613	-562	-1589	-570	-1685	-561	-1495	-396	-1460	-340
6000	-1950	-675	-1991	-667	-1934	-667	-1914	-671	-2020	-658	-1819	-479	-1771	-425
7000	-2251	-772	-2306	-763	-2234	-753	-2215	-759	-2327	-749	-2122	-565	-2062	-507
8000	-2576	-878	-2645	-863	-2545	-855	-2545	-852	-2665	-842	-2443	-656	-2371	-593
9000	-2877	-972	-2975	-947	-2835	-951	-2857	-951	-2985	-924	-2755	-746	-2673	-679
10000	-3164	-1073	-3310	-1040	-3103	-1036	-3170	-1043	-3295	-1009	-3047	-831	-2955	-760
0	-146	-108	-166	-101	-168	-108	-189	-81	-172	-75	-96	-1	-70	8
1000	-282	-92	-311	-110	-303	-90	-272	-105	-327	-97	-253	-92	-281	-27
2000	-575	-184	-615	-201	-595	-177	-560	-191	-630	-189	-553	-182	-577	-115
3000	-874	-280	-910	-293	-888	-269	-855	-276	-924	-279	854	-262	-859	-198
4000	-1149	-374	-1196	-379	-1167	-369	-1138	-380	-1221	-375	-1130	-340	-1128	-276
5000	-1435	451	-1488	-458	-1443	-445	-1423	-459	-1513	-452	-1430	-423	-1419	-361
6000	-1736	-544	-1794	-546	-1729	-529	-1705	-541	-1799	-523	-1714	-501	-1691	-438
7000	-2050	-643	-2120	-649	-2046	-643	-2033	-650	-2141	-639	-2030	-590	-1998	-525
8000	-2335	731	-2432	-727	2329	-729	-2329	-733	-2447	-720	-2330	-674	-2290	-609
9000	-2652	-842	-2779	-829	-2628	-827	-2644	-831	-2757	-809	-2610	-752	-2555	-682
10000	-2965	-955	-3142	-930	-2932	-938	-2997	-943	-3117	-915	-2942	-851	-2885	-780
0	-1	6	6	6	-2	0	-3	0	-1	7	-12	-8	-14	-8
5000	-1440	-456	-1485	-465	-1450	-450	-1423	-464	-1513	-456	-1428	-421	-1416	-366
10000	-2899	-904	-3066	-881	-2870	-895	-2933	-898	-3050	-865	-2915	-847	-2863	-780

NOTES: All strains are in microinches per inch
Electric resistance strain gages are CEA-03-125UT-350, Gage Factor 2.12
Ceramic Composition: Lanxide 90-X-89, SiC particulate reinforced alumina ceramic
End Closures: Titanium Hemishperical Bulkheads providing radial support
Cylinder Dimensions: 6.038 OD x 5.622 ID x 9.0 L x 0.208 in thick
Cylinder Weight: 1907 grams
Quality: No visually detectable defects

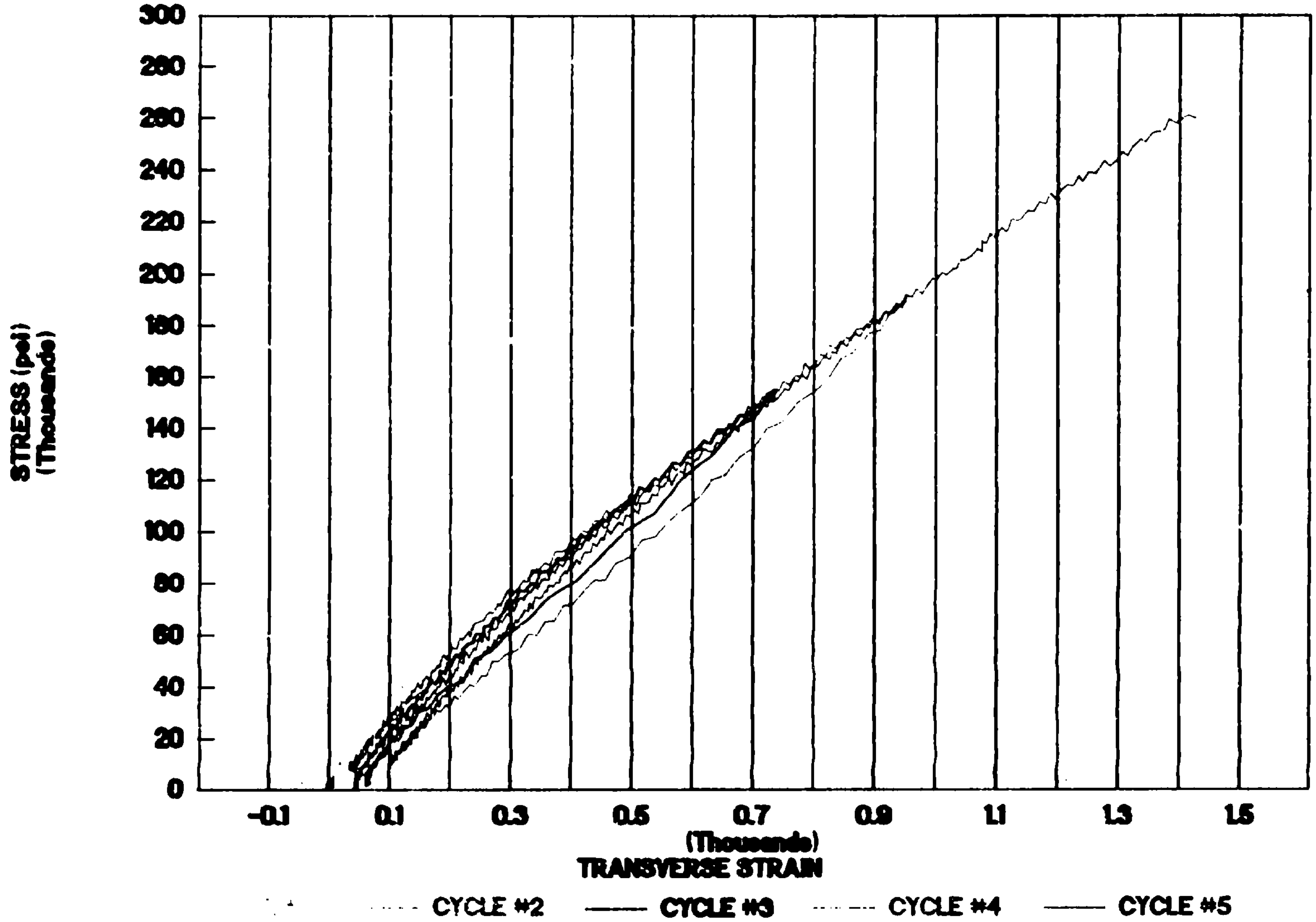

MODEL SCALE CYLINDER
LANXIDE® CYLINDER E
LOCATION: MIDBAY INTERIOR
O HOOP
Δ AXIAL
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
0
-2000
-4000
-6000
-8000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000

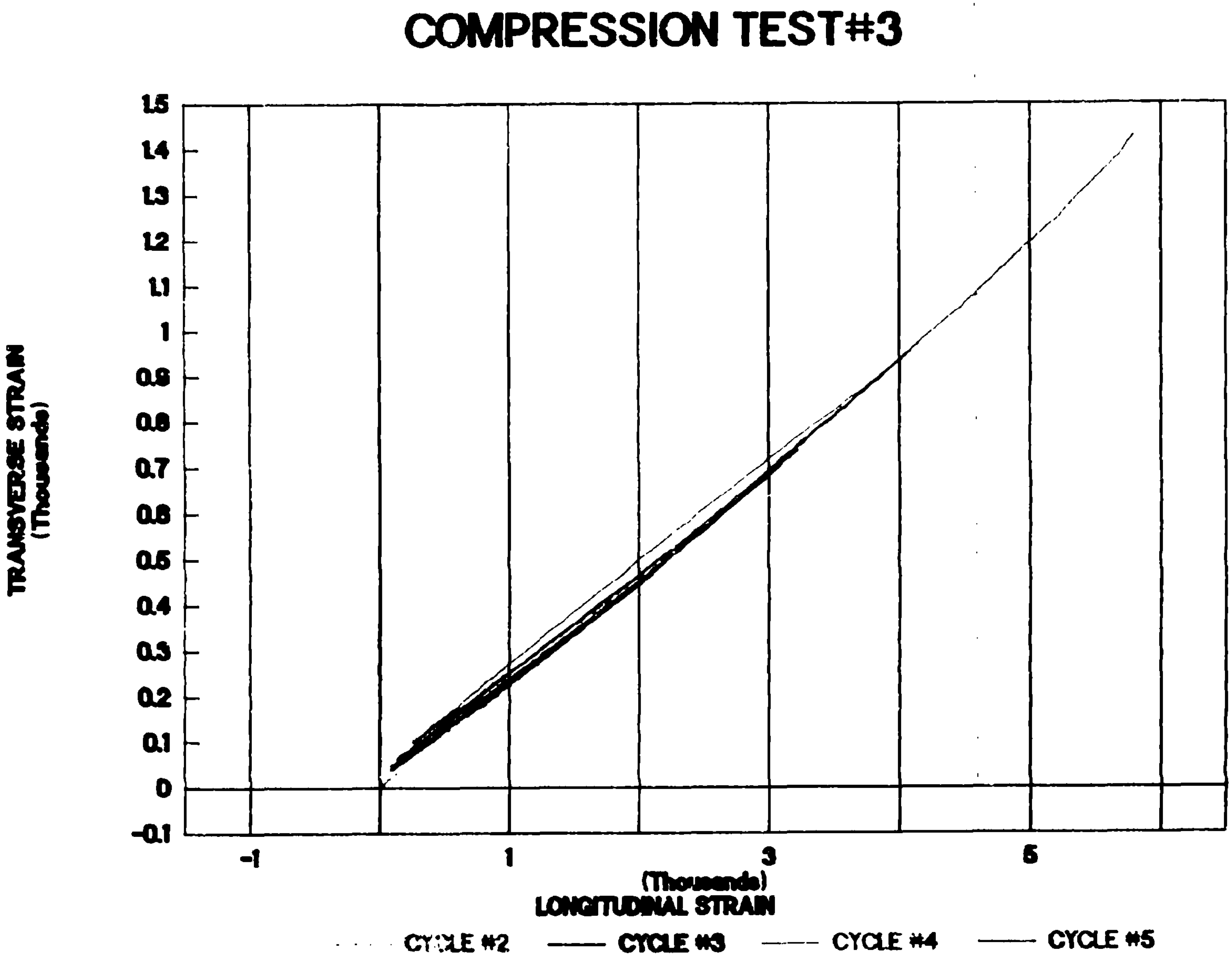

MODEL SCALE CYLINDER
LANXIDE® CYLINDER E
LOCATION: END INTERIOR
O HOOP
Δ AXIAL
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
0
-2000
-4000
-6000
-8000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000


MODEL SCALE CYLINDER
LANXIDE® CYLINDER E
AVERAGE STRAINS
PRESSURE, PSI
STRAIN, MICROINCHES/INCH
LOCATION: MIDBAY INTERIOR
HOOP
AXIAL


MODEL SCALE CYLINDER
LANXIDE® CYLINDER E
HYDROSTATIC PRESSURE, PSI
ACOUSTIC EVENTS X 10^2
NOTES:
CYCLE 1
CYCLE 2
TRANSDUCER AC175L
AMPLIFIER SETTING 80dB
LOCATION INSIDE VESSEL

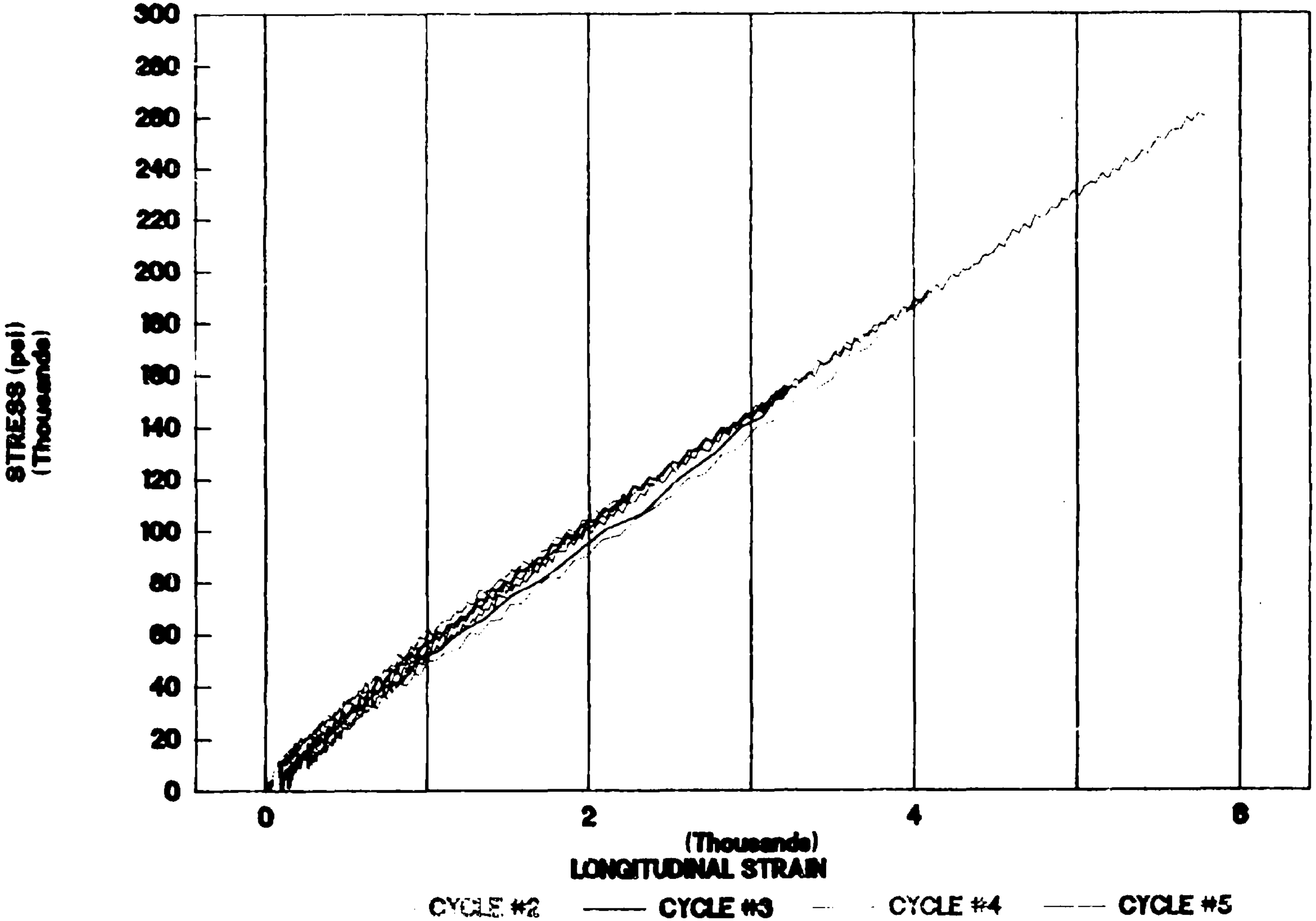
COMPRESSION TEST#3

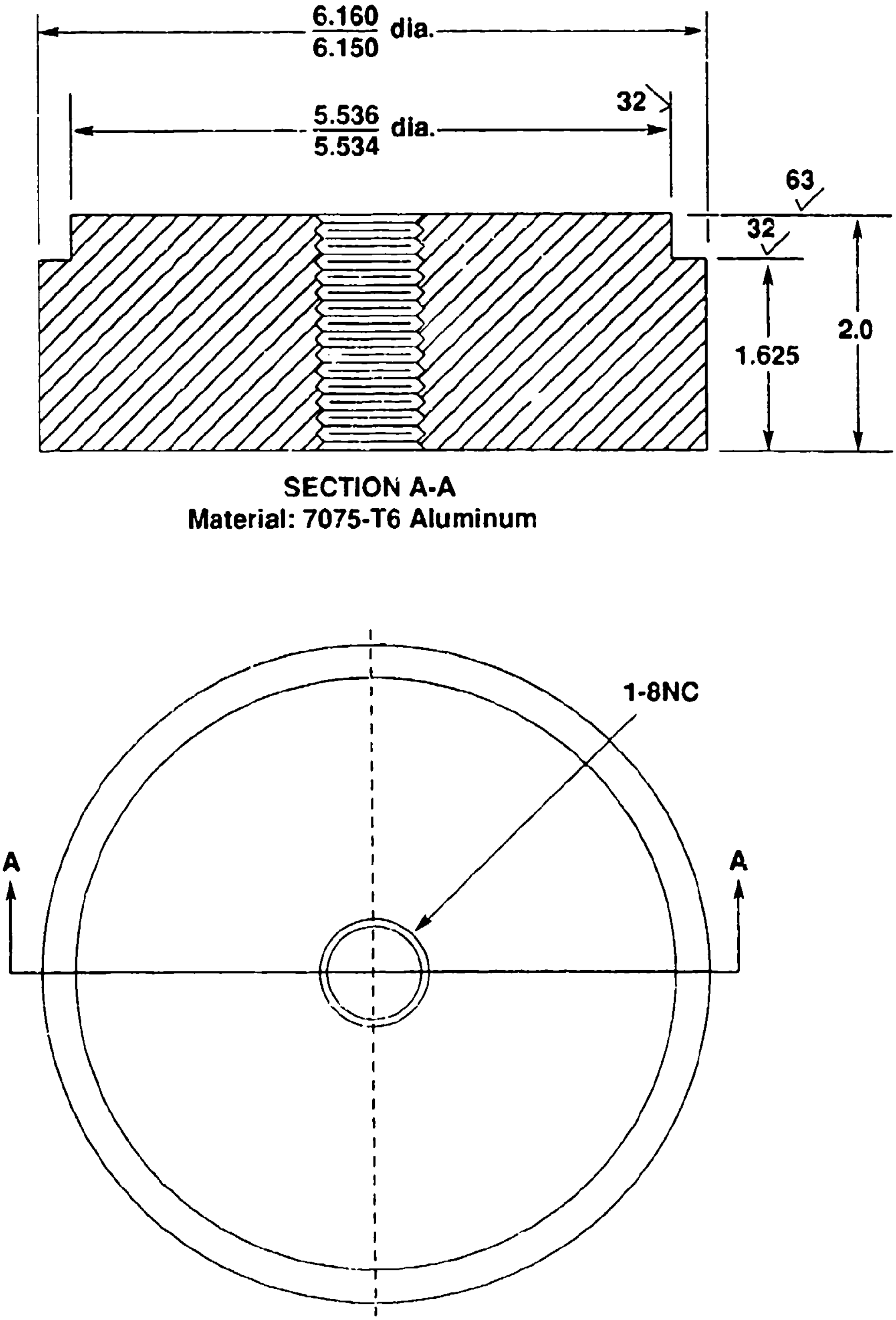




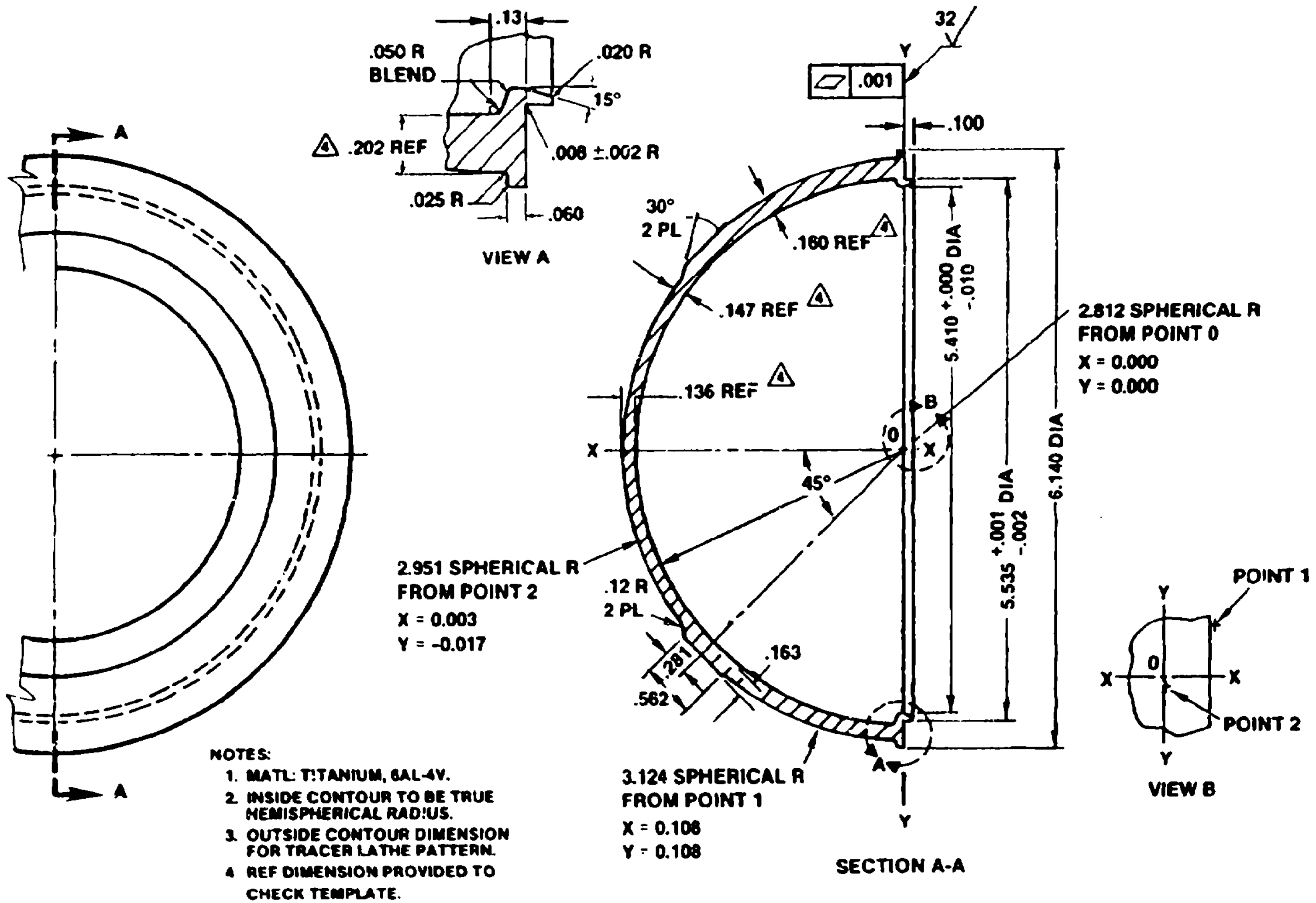
COMPRESSION TEST#3
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
TRANSVERSE STRAIN
(Thousands)
-1
1
3
5
(Thousands)
LONGITUDINAL STRAIN
CYCLE #2
CYCLE #3
CYCLE #4
CYCLE #5

COMPRESSION TEST#3

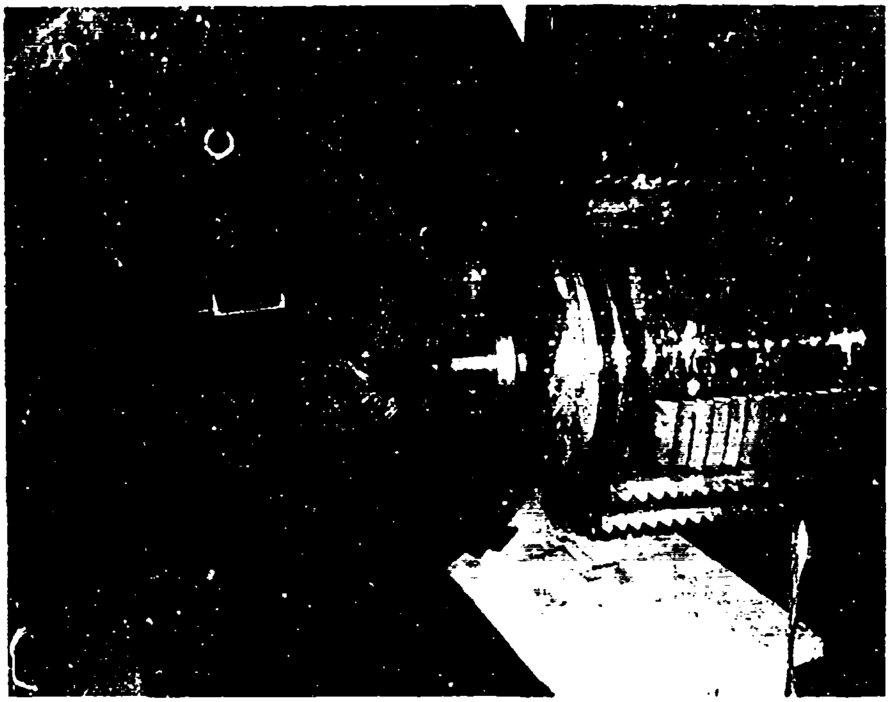




BULKHEADS FOR IMPLOSION TESTING
OF MODEL SCALE CYLINDERS



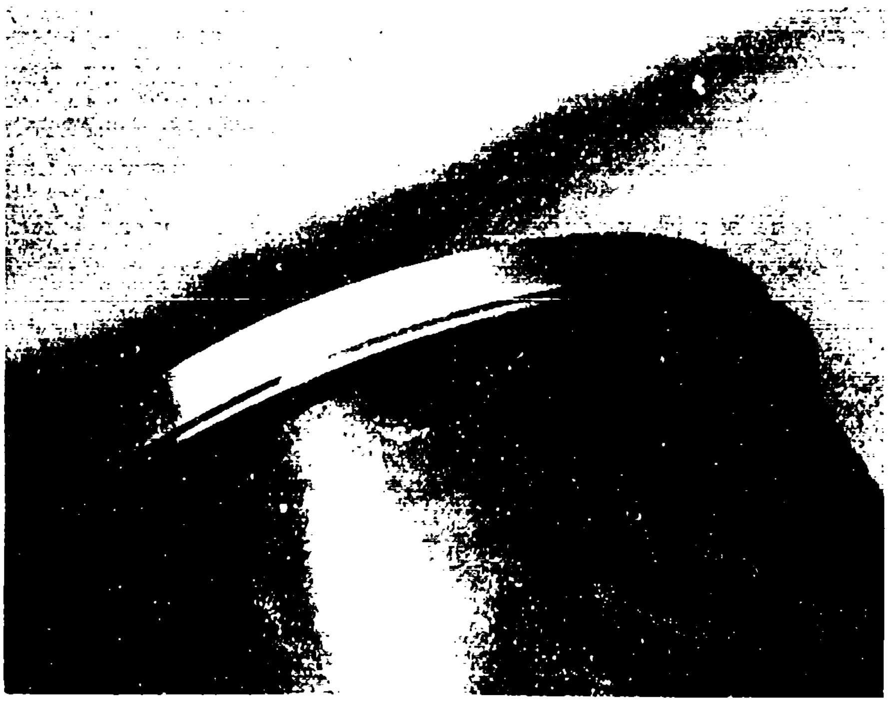
Ceramic pressure hull models 1 & 2 titanium end closure.



The converted 12-inch gun barrel used for pressure testing of the model scale ceramic housing assemblies.

Model scale ceramic cylinder after implosion due to material failure.

Model scale ceramic cylinder after implosion due to elastic instability (buckling).



Typical spalling failure of ceramic cylinder after repeated pressure cycling to 15,000 psi.

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13. ABSTRACT *(Maximum 200 words)*

Novel ceramic matrix composite tubes for deep submergence pressure vessel applications have been fabricated by the DIMOX™ directed metal oxidation process. This report details the processing information, hydrostatic test results, and mechanical test data.

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